PARTNER RESEARCH 2003 – 2013

PUBLIC SYMPOSIUM
MARCH 1, 2013
COSTA MESA, CALIFORNIA



Opinions, findings, conclusions and recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of PARTNER sponsor organizations.

March 1, 2013
Costa Mesa, CA

PARTNER
Partnership for Air Transportation Noise and Emissions Reduction

PARTNER 10 year Symposium (Morning)

PARTNER
10 YEARS
2003-2013

Lido Room, First Floor, Westin South Coast Plaza, Costa Mesa, CA

FRIDAY, March 1st, 2013

8:00 AM – 8:30 AM	*- Registration -*
8:30 AM – 8:45 AM	Welcome and 10 year PARTNER overview (Barrett)
8:45 AM – 9:00 AM	PARTNER contribution: Where we were 10 years ago, where we are today (Maurice)
9:00 AM – 9:45 AM	PARTNER sponsor comments (Moderator: Maurice) FAA: Hileman, TC: Simpson (remotely), NASA: Luck, Eckman
9:45 AM – 10:10 AM	*- Poster presentations and mid-morning break -*
10:10 AM – 11:00 AM	<u>Presentations on noise research (Chair: Miller)</u> • Noise propagation (Sparrow) • Noise annoyance research (Davies) • Research on the effects of aircraft noise on sleep (Basner)
11:00 AM – 11:40 AM	<u>Presentations on air quality and climate research (Chair: Miake-Lye)</u> • Air Quality and health impacts of aviation (Arunachalam) • Metrics for aviation effects on climate: What have we learned? (Wuebbles)
11:40 AM – 12:10 PM	<u>Presentations on tools and policy analysis (Chair: Roof)</u> • Introduction to tools (Roof) • Assessing the costs and benefits of aviation environmental policies (Mahashabde)

Agenda Symposium (Afternoon)

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FRIDAY, March 1st, 2013

12:10 PM – 1:10 PM	*- Lunch Break -*
1:10 PM – 2:00 PM	<u>Presentations on aircraft technology research (Chair: Barrett)</u> • Technology modeling and assessment (Kirby) • Metrics for an aviation CO2 standard (Bonnefoy / Kirby)
2:00 PM – 2:20 PM	<u>Presentation on operations research (Chair: Luck)</u> • Operations research under PARTNER (Hansman, remotely)
2:20 PM – 2:40 PM	*- Poster presentations and mid-afternoon coffee break -*
2:40 PM – 3:20 PM	<u>Presentations on fuels and emissions research (Chair: Hileman)</u> • PARTNER leading the way in alternative emissions characterization (Whitefield) • Environmental sustainability of alternative fuels for aviation (Barrett)
3:20 PM – 4:20 PM	Stakeholder panel: What have we accomplished and what remains to be done? (Baughcum, McGrann,, Miller, Miake-Lye, Pohle, Moderator: Maurice)
4:20 PM – 4:30 PM	Closing remarks (Maurice)

PARTNER RESEARCH, 2003 – 2013
PUBLIC SYMPOSIUM

Introduction & PARTNER overview

Prof. Steven Barrett
Associate Director, PARTNER
Department of Aeronautics and Astronautics, MIT

10th Year Public Symposium
March 1, 2013
Costa Mesa, CA

PARTNER
Partnership for Air Transportation Noise and Emissions Reduction

Agenda

PARTNER
10 YEARS
2003-2013

1. Organization
2. Activities
3. Impacts
   a. On Industry, Policy and Academia
   b. On Workforce Development
4. PARTNER today

Agenda

PARTNER
10 YEARS
2003-2013

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PARTNER vision

The Partnership for Air Transportation Noise and Emissions Reduction is a cooperative research organization that advances knowledge and practice in aviation, energy and environment.

Our vision is to be a world-class research organization…



…fostering breakthrough technological, operational, and policy advances;

…leveraging a broad range of stakeholder capabilities;

…to align the trajectory of aerospace technology and policy development with the need to mitigate environmental impacts and improve energy security.

PARTNER universities
12 schools, 263 students

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- **Boston U.**
- **Georgia Institute of Technology**
- **Harvard U.**
- **MIT***
- **Missouri U. of Science and Technology***
- **Pennsylvania State U.***
- **Purdue U.***
- **Stanford U.**
- **U. of Illinois at Urbana-Champaign**
- **U. of North Carolina**
- **U. of Pennsylvania**
- **York U.**



* Founding Members of PARTNER

Broadened internal research program

PARTNER
10 YEARS
2003-2013

DOT FAA – Office of Environment and Energy, Air Traffic Organization

NASA – Vehicle Systems Program

Transport Canada Transports Canada

Environmental Protection Agency

DOD – Air Force Research Laboratory, Defense Logistics Agency - Energy

- $2.7M for FY03/04
- $4.1M for FY05
- $6.7M for FY06
- $6.1M for FY07
- $6.6M for FY08
- $8.6M for FY09
- $9.3M for FY10
- $4.9M for FY11
- $7.1M for FY12

50:50 Cost sharing for all federal grant funds, "except that the Administrator may increase such [federal] share to a maximum of 75 percent of the costs for a fiscal year if the Administrator determines that a center would be unable to carry out the authorized activities described in this section without additional funds.'' -- FAA Modernization and Reform Act of 2012 (H.R. 658)

Cost Share

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10 YEARS
2003-2013

- From 2003 to January 2012, a total non-federal cost share of $35.7M has been contributed to PARTNER
- This has lead to significant collaboration between the PARTNER schools, industry and international research programs
- Our cost share partners span the following segments of the aviation industry:
  - Research institutions
  - Fuel providers
  - Aircraft and engine manufacturers
  - Airlines and their associations

Advisory board: 55 organizations

Industry/professional/community (44), FAA (6), NASA (2), DOD (2), and Transport Canada (1)

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- Aerodyne Research Inc.
- Aerospace Industries Association
- Airbus
- Air Line Pilots Association, Intl
- Airlines for America
- Airports Council International – North America
- American Institute of Aeronautics and Astronautics
- Bay Area Air Quality Management District
- Boeing
- Bombardier
- Ceres, Inc.
- Cessna Aircraft
- City of College Park, GA
- Commercial Aviation Alternative Fuels Initiative
- CSSI Incorporated
- Delta Airlines
- FAA Airports and Environmental Law Division (FAA AGC)
- FAA ATO Airspace Services Division (FAA AJV-1)
- FAA Centers of Excellence (FAA ANG-A12)
- FAA Office of Airports (FAA APP-400)
- FAA Flight Standards (FAA AFS)
- FAA Office of Environment and Energy (FAA AEE)
- Federal Interagency Committee on Aviation Noise
- Finegold & So Consultants
- General Electric Aircraft Engines
- Gevo, Inc.
- Gulfstream Aerospace
- Harris, Miller, Miller & Hanson
- Honeywell UOP, LLC
- International Airline Passengers Association
- Lockheed Martin Aeronautics Co.
- Massachusetts Port Authority
- Metron Aviation
- Metropolitan Washington Airport Authority
- MITRE-CAASD
- NASA Aeronautics Research Mission Directorate
- NASA Science Mission Directorate
- National Air Traffic Controllers Association
- National Organization to Insure a Sound-controlled Environment
- O'Hare Noise Compatibility Commission
- Palisades Citizens Association
- Port of Portland
- Pratt & Whitney
- Regional Airport Authority of Louisville and Jefferson County
- Rolls Royce
- San Francisco International Airport/Community Roundtable
- Snecma
- Tetra Tech AMT
- Transport Canada
- United Parcel Service Airlines
- US DOD – Air Force Research Laboratory
- US DOD – Defense Logistics Agency (DLA) Energy
- US DOT – Volpe Nat'l Transportation Systems Center
- US Environmental Protection Agency – National Risk Management Research Laboratory
- Wyle Laboratories

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Projects: Emissions

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2003-2013

29 ACTIVE PROJECTS

Emissions

9 | Measurement of Emissions (completed)

11 | Health Impacts of Aviation-Related Air Pollutants

12 | Emissions Atmospheric Impacts

15 | Aircraft Impacts on U.S. Local and Regional Air Quality (completed)

16 | Investigation of Aviation Emissions Air Quality Impacts

20 | Emissions Characteristics of Alternative Aviation Fuels

27 | Environmental Cost-benefit Analysis of Ultra Low Sulfur Jet Fuels (completed)

29 | Emissions Characteristics of Modern/Future Aviation Sources

33 | Isotopic Analysis of Airport Air Quality (completed)

34 | International Collaborative Emissions Studies (completed)

37 | Non-volatile Particulate Matter – SAE E31 Aerospace Recommended Practice Research

41 | Aircraft Black Carbon Emissions at Cruise (completed)

45 | Aviation System Air Quality Performance Analysis

46 | Aviation System Global Climate Performance Analysis

Projects: Noise

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2003-2013

Noise

1 | Low Frequency Noise Study (completed)

2 | Source Emission and Propagation

8 | Sonic Boom Metrics

10 | Outreach

19 | Health Effects of Aircraft Noise (completed)

24 | Noise Exposure Response: Annoyance

25 | Noise Exposure Response: Sleep Disturbance

26 | Sound Transmission Indoors — Integrated Windows (completed)

35 | Open Rotor Noise Impact On Airport Communities (completed)

38 | Sound Transmission Indoors — Study of Whole Houses

44 | Aviation Noise Effects on the Elderly

Projects: Operations

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2003-2013

Operations

4 | Continuous Descent Arrival (completed)

5 | En Route Traffic Optimization to Reduce Environmental Impact (completed)

6 | Land Use Management and Airport Controls (completed)

13 | Lateral Alignment in Complex Systems (completed)

18 | Reduced Vertical Separation Minimums (completed)

21 | Airport Surface Movement Optimization

22 | Objective Measures to Support Airspace Management (completed)

23 | Network Restructuring Scenarios for ATO Forecasts (completed)

32 | Near-Term Operational Changes

39 | Terminal Area Aircraft Simulation Tools Evaluation

40 | Continuous Descent Arrival National Operational Feasibility (completed)

43 | Analysis of Mission Specifications

Projects: Interdependencies

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2003-2013

Interdependencies and policy assessment

3 | Valuation and Trade-offs of Policy Options

14 | Environmental Design Space

30 | Metrics for an Aviation CO_2 Standard

31 | Understanding the Relationship Between Aviation Economics and the Broader Economy (completed)

36 | EDS Capability Demonstration for Assessing the CLEEN Program

42 | Development and Evaluation of Climate Metrics

48 | Development of a Distributed Approach to System Level Uncertainty Quantification

Projects: Alternative Fuels

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2003-2013

Alternative Fuels

17 | Alternative Fuels (completed)

20 | Emissions Characteristics of Alternative Aviation Fuels

27 | Environmental Cost-benefit Analysis of Ultra Low Sulfur Jet Fuels (completed)

28 | Environmental Cost-benefit Analysis of Alternative Jet Fuels

47 | Alternative Jet Fuel Sustainability

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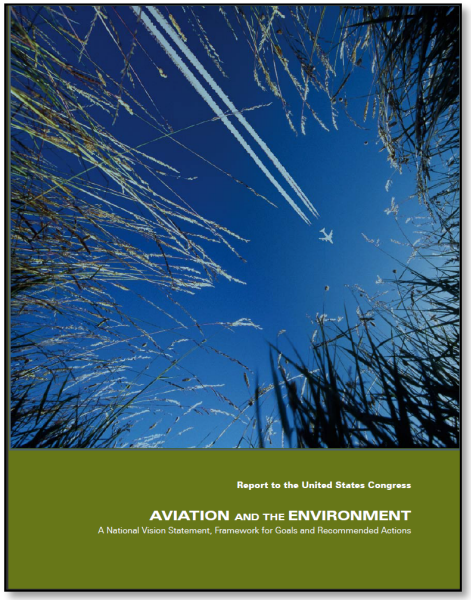
Impacts: Publications and Outreach

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2003-2013

- PARTNER researchers have released hundreds of archival publications (just MIT's PARTNER group alone published more than 50 journal publications since 2007)
- 31 reports in own report series



- PARTNER investigators submitted a report on Aviation and the Environment to the United States Congress
- PARTNER researchers were part of the U.S. Delegation for COP15

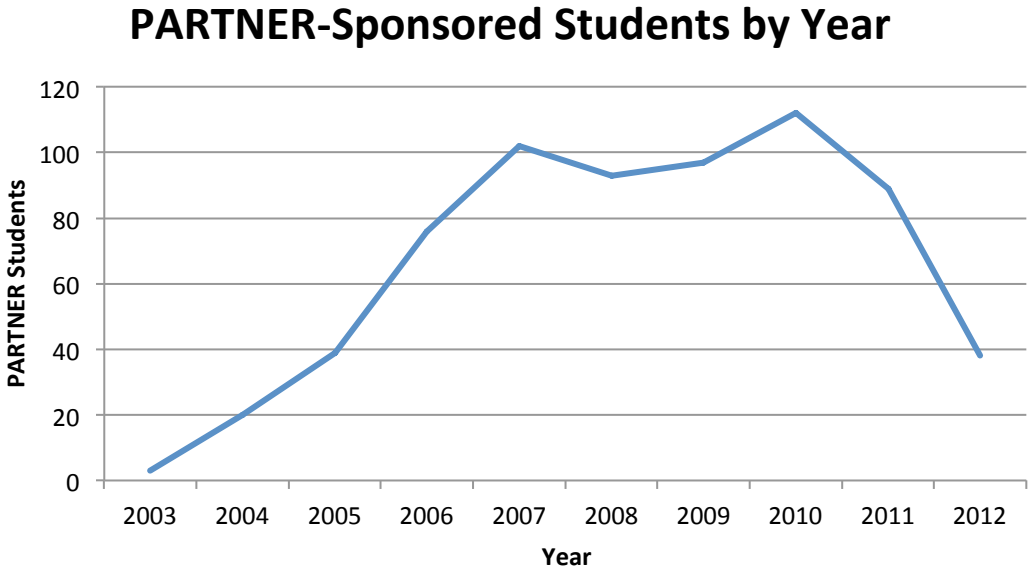


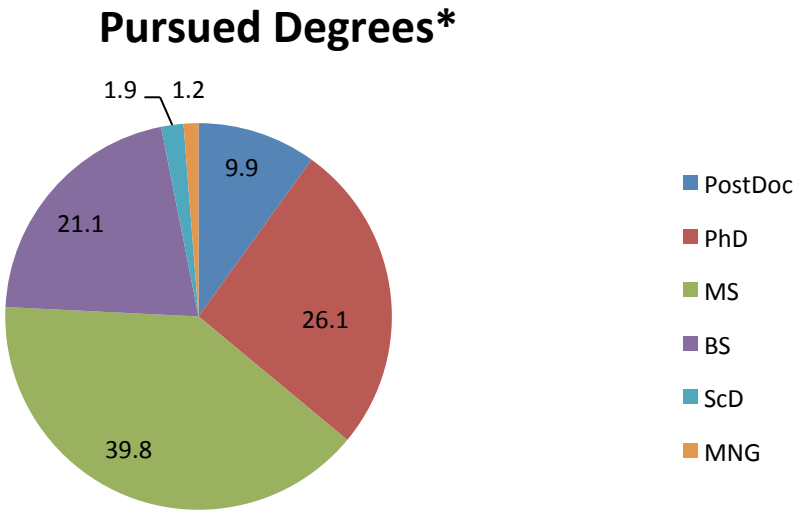
PARTNER's impact

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- The Symposium today is all about impact
- Symposium showcases various projects and their contribution for academia, policy-making and stakeholders in the following areas:
  - Noise
  - Climate and air quality
  - Tools and policy analyses
  - Aircraft technology
  - Operations
  - Fuels and emissions

Impacts on Workforce Development (1 of 4)





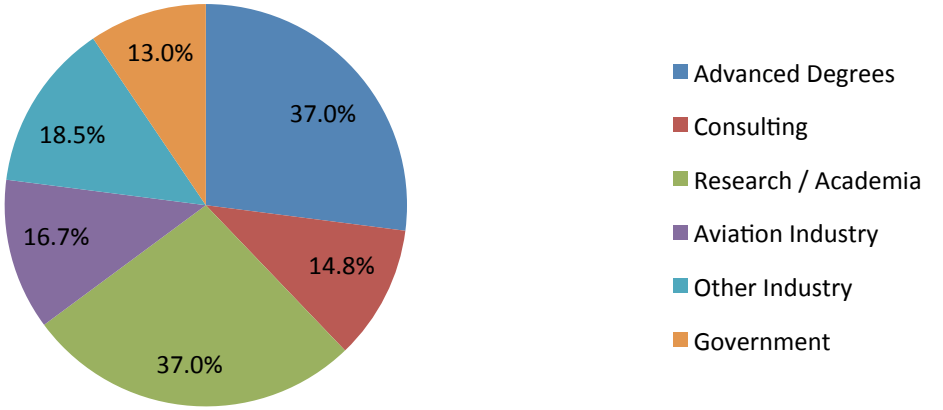
* Based on information for 161 out of 263 students

- The number of PARTNER-sponsored students fluctuates with our funding levels
- In total, 263 students have been supported since 2003
- Most PARTNER students pursue graduate degrees (MS and PhD)

Impacts on Workforce Development (2 of 4)

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10 YEARS
2003-2013

Industries in which PARTNER Graduates Work*



* Based on information for 73 out of 201 graduates

- We estimate that 70% of former PARTNER students and post-docs are now active in aviation, energy and the environment.

- More than 2/3 of the PARTNER graduates remain in academia for an advanced degree or become faculty or research staff.

- About 32% of those who leave school start their professional career at a PARTNER advisory board member or a sponsor.

Impacts on Workforce Development (3 of 4)



Elza Brunelle-Yeung

- RA at PARTNER
- MS in 2009
- Research on "*The impacts of aviation emissions on human health through changes in air quality and UV irradiance"*

Now: Senior Analyst at the Strategy and Business Development Department of Bombardier Aerospace



Matthew Pearlson

- RA and Research Specialist at PARTNER
- MS in 2011
- Research on "A *Techno-Economic and Environmental Assessment of HRJ Fuels"*

Now: Entrepreneur



Dr. Philippe Bonnefoy

- Postdoc at PARTNER
- Left PARTNER in 2010
- Research on *"Metrics for a CO_2 Standard for Aviation"*

Now: Lead Associate at Booz Allen Hamilton

Impacts on Workforce Development (4 of 4)

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2003-2013



Prof. Karen Marais

- Postdoc at PARTNER
- Left PARTNER in 2007
- Research on "*Valuation and Trade-offs of Policy Options*"

Now: Assistant Professor, School of Aeronautics and Astronautics, Purdue University



Chris Sequeira

- RA at PARTNER
- MS in 2008
- Research on "*An assessment of the health implications of aviation emissions regulations*"

Now: Project Manager, FAA Office of Environment and Energy



Dr. Douglas Allaire

- RA, Postdoc at PARTNER
- PhD in 2009, Postdoc ended 2010
- Research on *"Uncertainty Assessment of Complex Models with Application to Aviation Environmental Systems"*

Now: Research Scientist, Dept. of Aeronautics & Astronautics, MIT

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Inputs → PARTNER → Outputs

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Inputs

- About $6M of direct federal funding per year
- Cost-share from non-federal sources
- Project and program management efforts at AEE and MIT

Outputs

- Development of operational approaches that reduce fuel costs and environmental impacts
- Scientific assessment of environmental policies and technologies
- Comprehensive assessment of alternative fuels, providing guidance for policy-makers and industry
- Education of 263 students, 70% remain as additional workforce capacity in aviation, environment, and energy

PARTNER today

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- PARTNER addresses critical needs for aviation, energy and the environment
- Strong team (200+ people)
- Nearing 10 years of operation
- Significant international collaborations
- World-class contributions, real-world impact
- Excellent support from sponsors and Advisory Board members
- An leading forum for aviation and the environment


WELCOME!
We look forward to our discussions today!

PARTNER Research and its Relationship to FAA Environment and Energy Goals



Presented to: 10 Year PARTNER Public Symposium

By: Dr. James Hileman
Office of Environment and Energy
Federal Aviation Administration

Date: March 1, 2013

Location: Costa Mesa, California

Aviation, Environment and Energy

- Aviation impacts affect community noise footprints, air quality, water quality, and the global climate
- Trends show environmental impacts from aircraft noise and aviation emissions will be a critical constraint on capacity growth
- The stringency of environmental standards and efforts to mitigate environmental impacts are increasing
- Fundamental changes are ongoing in energy markets.



The challenge is to increase mobility with reduced environmental impacts and enhanced energy efficiency, sustainability and security.

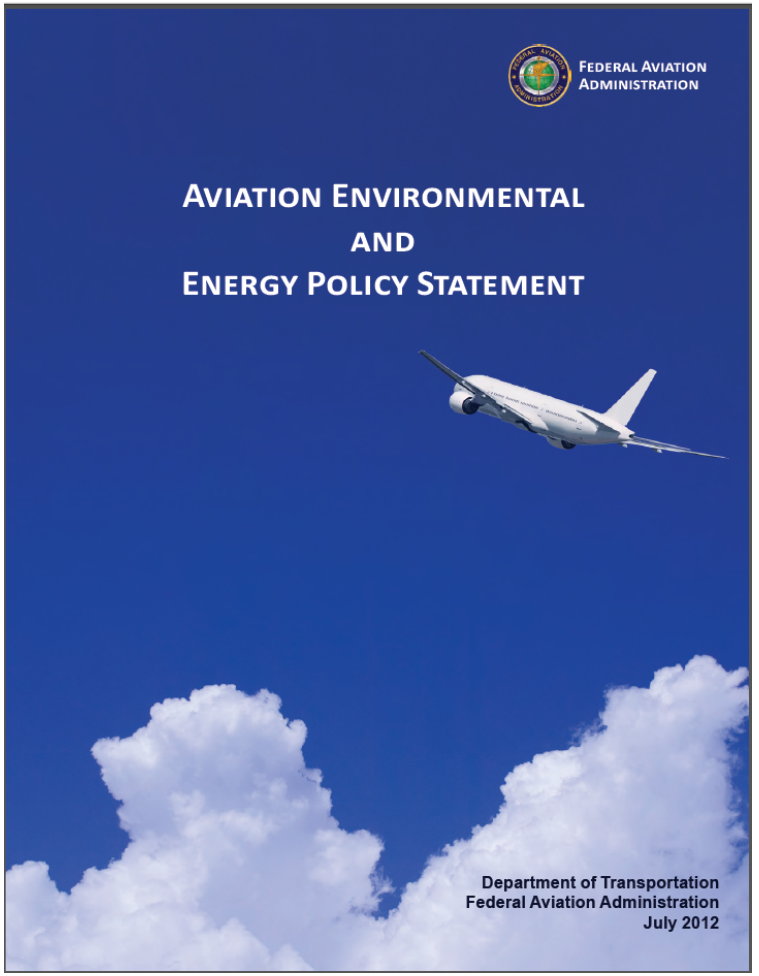
Vision and Principles

Vision:

Environmental protection that allows sustained aviation growth

Guiding Principles:

1. Limit and reduce future aviation environmental impacts to levels that protect public health and welfare.
2. Ensure energy availability and sustainability.



Aviation E&E Policy Statement (Federal Register 77-141, 2012): http://www.faa.gov/about/office_org/headquarters_offices/apl/environ_policy_guidance/policy/media/FAA_EE_Policy_Statement.pdf

Environment & Energy Goals and Metrics

Aspect	Goal[1]	Performance Metric[2]
Noise	Reduce the number of people exposed to significant noise around U.S. airports in absolute terms, notwithstanding aviation growth, and provide additional measures to protect public health and welfare and our national resources.	The U.S. population exposed to significant aircraft noise around airports has been reduced to less than 300,000 persons by 2018.
Air Quality	Achieve an absolute reduction of significant air quality health and welfare impacts attributable to aviation, notwithstanding aviation growth.	Aviation emissions contribute 50 percent less to significant health impacts in 2018 using a 2005 baseline.
Energy	Improve National Airspace System (NAS) energy efficiency by at least two percent per year, and develop and deploy alternative jet fuels for commercial aviation.	Improve NAS energy efficiency (fuel burned per miles flown) by at least 2 percent annually. One billion gallons of renewable jet fuel is used by aviation by 2018.
Climate	Limit the impact of aircraft CO2 emissions on the global climate by achieving carbon neutral growth by 2020 compared to 2005, and net reductions of the climate impact from all aviation emissions over the longer term (by 2050).	Aviation emissions are on a trajectory for carbon neutral growth by 2018, using a 2005 baseline.

Source:
1. Aviation Environmental and Energy Policy Statement (2012)
2. Aspirational Goals from FAA Destination 2025

AEE Research Overview

Characterize the Problem and Assess Risk:

- Improve our scientific understanding of E&E constraints
- Incorporate this scientific knowledge into an integrated tool suite that can characterize the system, assess the risk and inform development of potential mitigation options

Develop mitigation solutions:

- Airframe and engine technologies
- Sustainable alternative jet fuels
- Clean, quiet and energy efficient operational procedures
- Policy measures

Manage system performance:

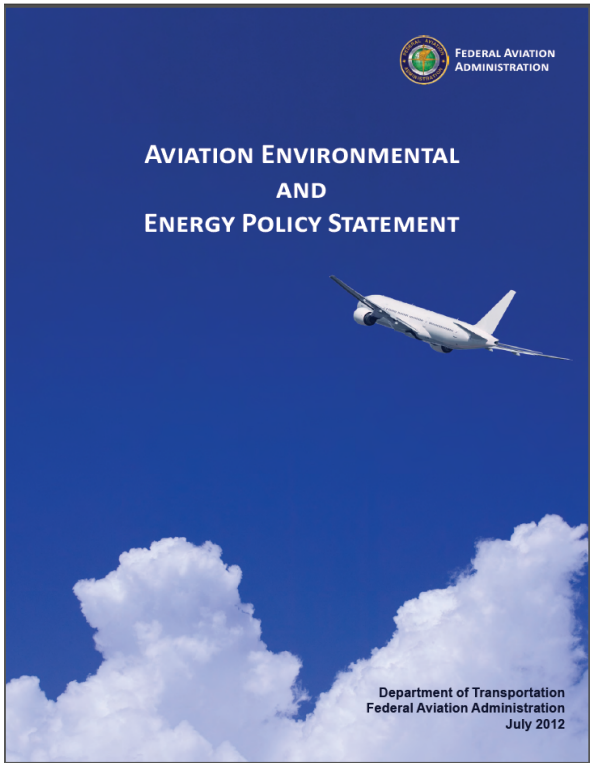
- Integrated analysis that engages a wide range of stakeholders to understand the current and future state of the aviation system
- Utilize knowledge to provide guidance on system improvements

E&E Strategy

Environmental protection that allows sustained aviation growth

NextGen Five-Pillar Environmental Approach

- P1: Improved Scientific Knowledge and Integrated Modeling
- P2: New Aircraft Technologies
- P3: Sustainable Alternative Aviation Fuels
- P4: Air Traffic Management Modernization and Operational Improvements
- P5: Policies, Environmental Standards, and Market Based Measures



Mapping of Environmental Goals and Pillars

Pillars → / *Goals* ↓	P1		P2	P3	P4	P5
	Scientific Knowledge	Integrated Modeling	Aircraft Technologies	Alt Jet Fuel	ATM Mod & Ops Imprvment	Policy Measures
NOISE: Reduce significant noise impact	X	X	X		X	X
AIR QUALITY: Reduce significant air quality impact	X	X	X	X	X	X
ENERGY: Improve NAS energy efficiency	X	X	X	X	X	X
ENERGY: Develop sustainable alternative fuels	X	X		X		X
CLIMATE: Reduce GHG emissions and their impacts	X	X	X	X	X	X

PARTNER Research and the Five Pillar Strategy

PARTNER is an integral part of the FAA environment and energy research program

- **Pillar 1**: Improved Scientific Knowledge and Integrated Modeling
  PARTNER Projects 1, 2, 3, 8, 9, 11, 12, 15, 16, 19, 24, 25, 26, 27, 29, 33, 34, 35, 37, 38, 41, 42, 43, 44, 45, 46, 48
- **Pillar 2**: New Aircraft Technologies
  PARTNER Projects 8, 14, 35, 36, 43
- **Pillar 3**: Sustainable Alternative Aviation Fuels
  PARTNER Projects 17, 20, 27, 28, 34, 47
- **Pillar 4**: ATM Modernization and Operational Improvements
  PARTNER Projects 4, 5, 18, 21, 22, 23, 32, 39, 40
- **Pillar 5**: Policies, Environmental Standards, and Market Based Measures
  PARTNER Projects 6, 10, 30, 31, 43

PARTNER Accomplishments – Last 12 Months

- Instrumental in developing an internationally accepted CO2 Metric System.
- Provided cost benefit analysis for new ICAO CAEP noise stringency.
- Provided life cycle greenhouse gas emissions analysis that was instrumental in the inclusion of a new alternative jet fuel pathway within EPA's RFS2 program.
- Conducted particulate matter measurements that support development of an internationally accepted aviation PM measurement system.
- Developed surface movement model and congestion management approach for departure metering strategies to reduce surface congestion.
- Developed robust modeling capabilities to discern incremental health and climate impacts due to aviation emissions.
- Evaluated the environmental benefits of technologies being developed under the FAA Continuous Lower Emissions Energy and Noise (CLEEN) technology maturation program.

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Propagation

(Selected work from PARTNER Projects 1, 2, and 8.)

Presented by: Dr. Victor W. Sparrow, Penn State

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Motivation

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Propagation is how sound gets from an aircraft to a listener on the ground.





Challenge

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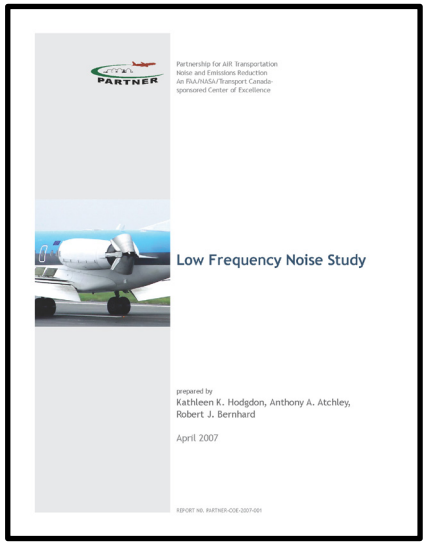
- Improve our understanding of propagation and how to improve prediction models.

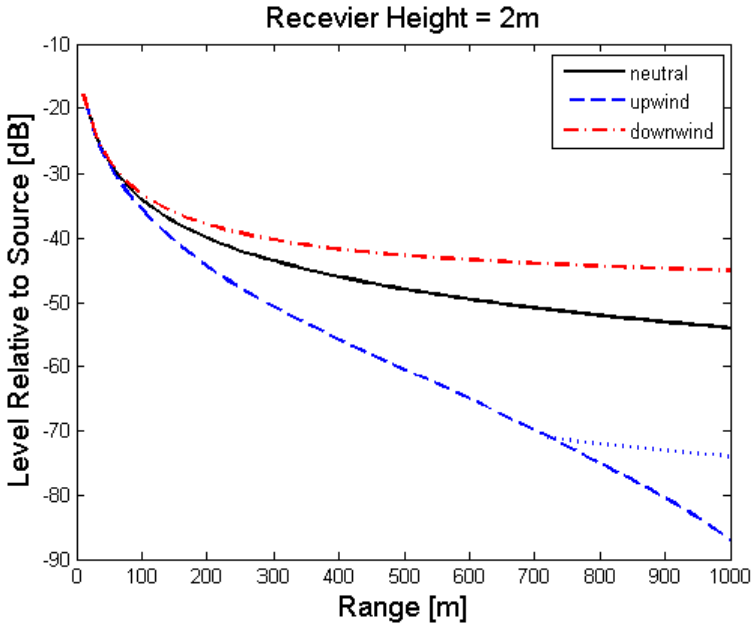
  Important factors are:
  - Ground surface
  - Atmosphere wind profile
  - Atmosphere temperature profile
  - Atmosphere humidity profile
  - Terrain
  - Terrestrial objects (e.g., buildings, mountains)
  - Turbulence
  - Aircraft parameters
  - Interface with noise sources [not this talk]
  - Interface with sound transmission [not this talk]

Initial Research

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- Once, there was a Project 1:



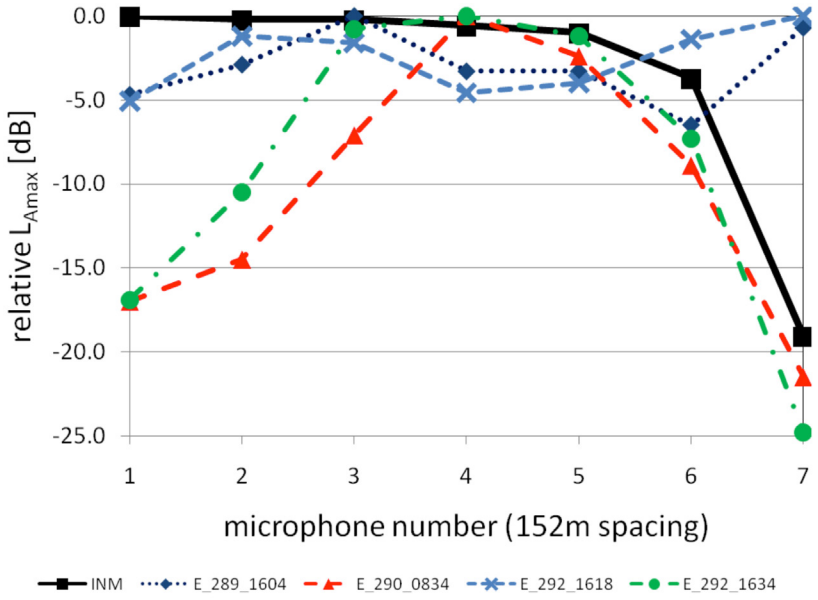


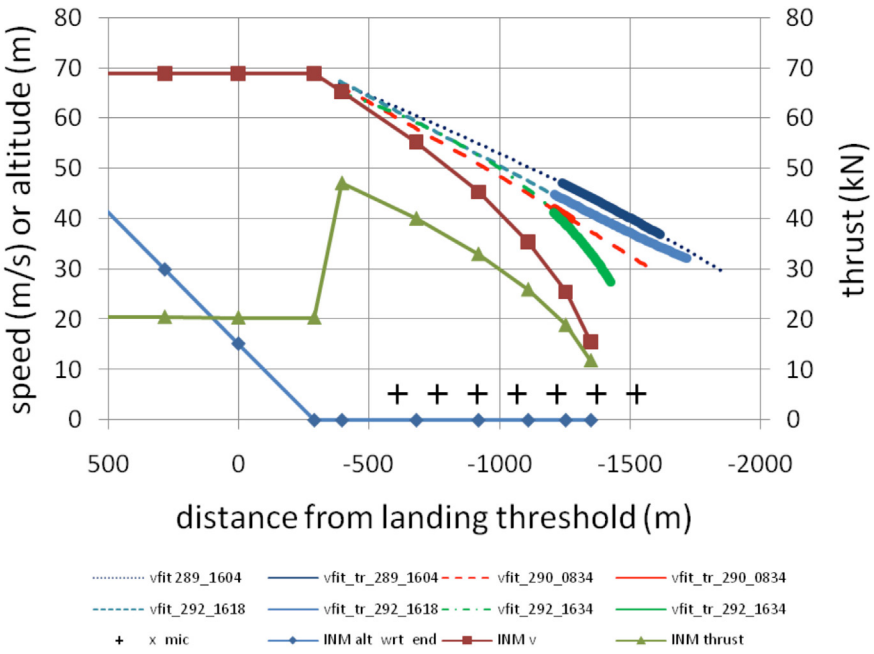
- 50 Hz calculation between 2 m height source and receiver
- At 1 km range, note the 45 dB difference depending on whether upwind or downwind.

http://mit.edu/aeroastro/partner/projects/project1.html

Thrust Reverser Research

- Atchley et al. presentation at Internoise, August 2009
  - Agreement between INM and experimentally observed TR noise levels can be improved by better matching of aircraft speed and TR deployment profiles



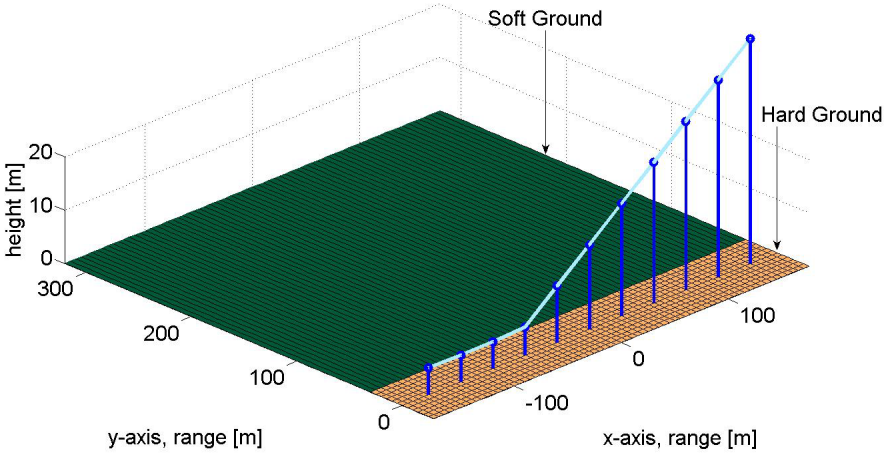


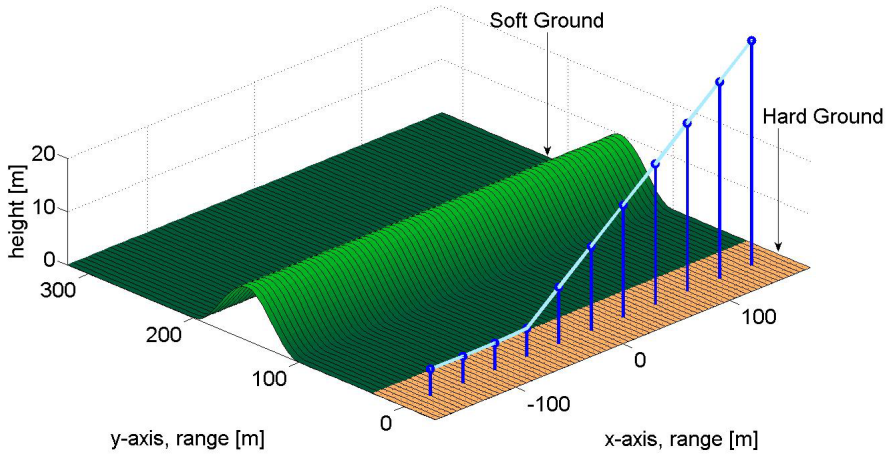
A. Atchley, R. Carbo, B. Dunkin, E. Boeker, H. He,
"Predictions of near runway thrust reverser noise," Proc. Internoise 2009,
(Institute of Noise Control Engineering, Washington, DC, 2009).

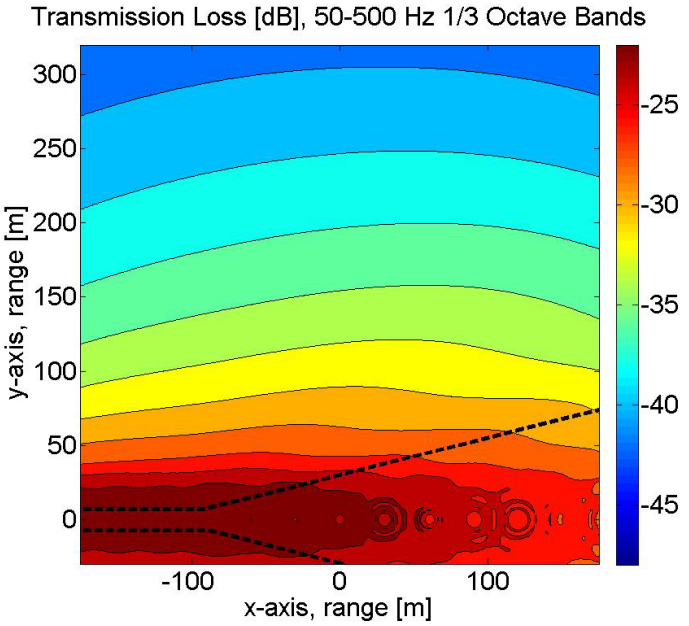
Research Using Parabolic Eq. Model: Adding Range-Dependent Effects

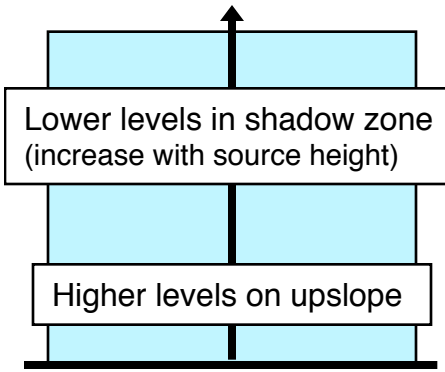
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2003-2013

• Simple take-off flight path • Flat and uneven terrain	• Downward refracting atmosphere $c = c_0 + b^* \ln(z/z_0+1)$, $b = 1$ m/s	• Ground Impedance Discontinuity – Hard (tan): 20,000 cgs Rayls – Soft (green):150 cgs Rayls



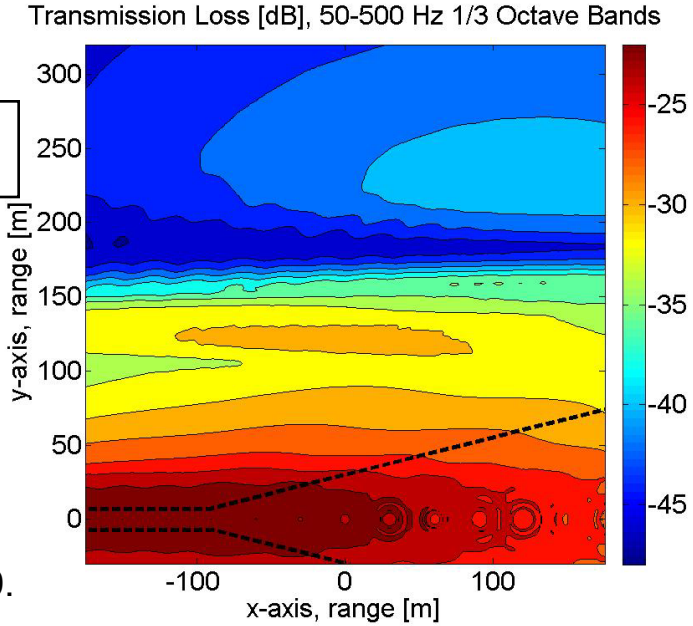






Effects of Hill

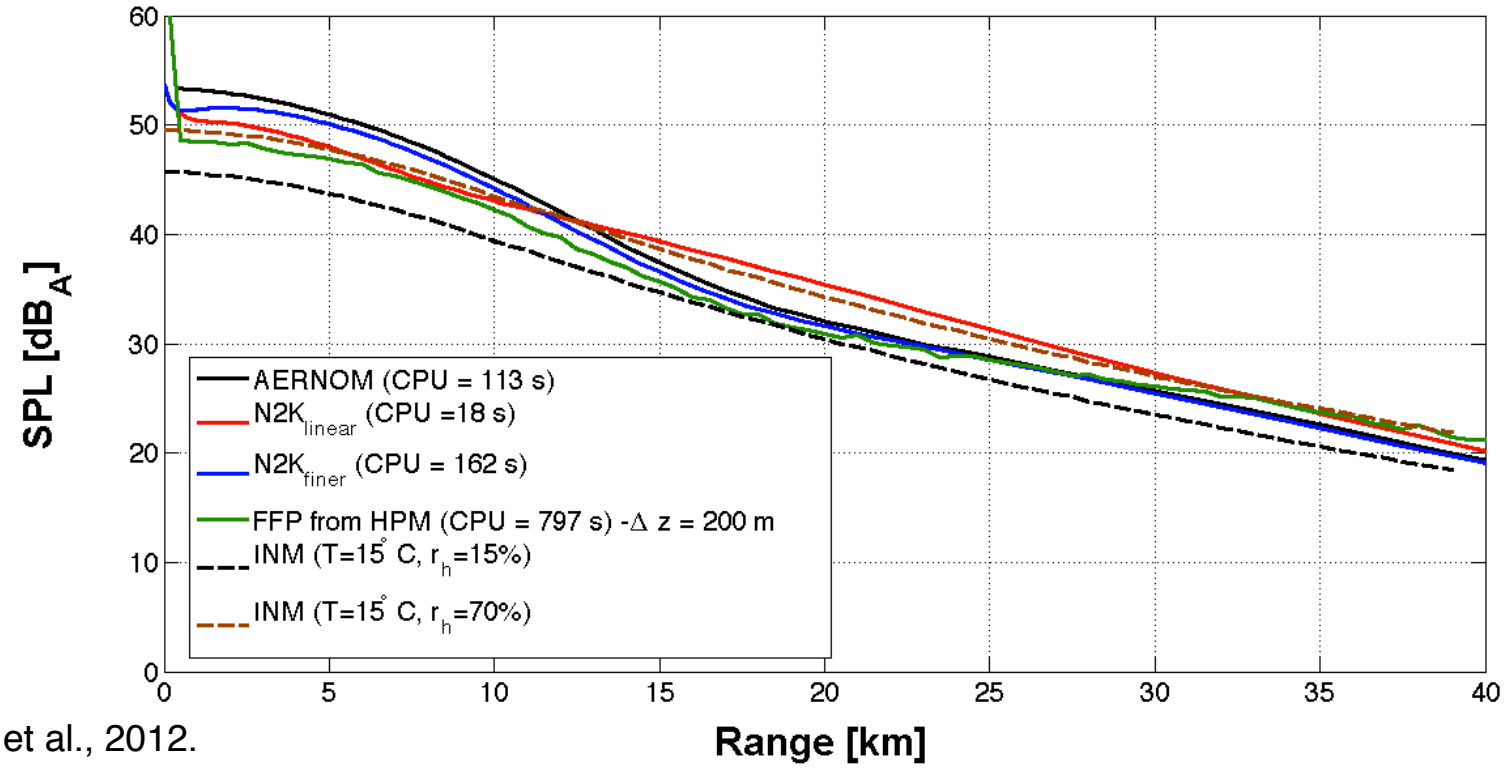
Rosenbaum, et al., 2010.



Research on En-route Noise: INM vs. Other Software

PARTNER
10 YEARS
2003-2013

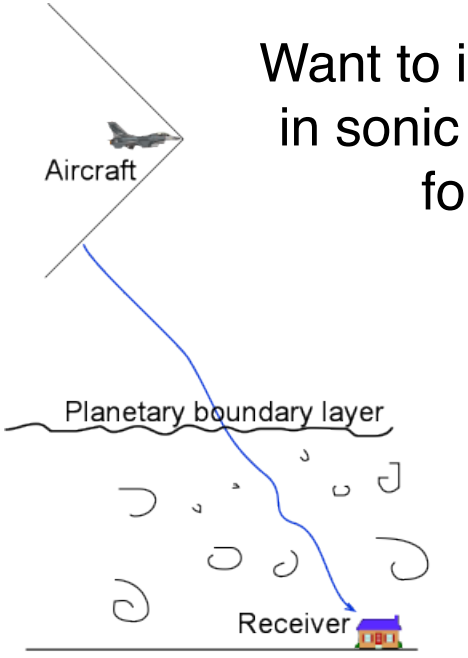
- $L_{A,max}$ [dB_A] vs. range in downwind refracting plane
- Stationary point source at z_s=10 km
- Temperature & humidity profiles from 2004 Bass/Sutherland paper
- B 777 1/3 OB spectrum retro fitted from INM NPD curves
- Linear wind speed profile: $v(z) = 3 \times z$ where *z* in km [not applicable in INM]
- INM inputs: 15 °C, various RH tested, 1 m long segment [CPU ≈ 5 s]



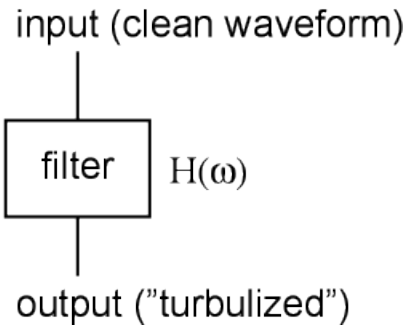
Poulain, et al., 2012.

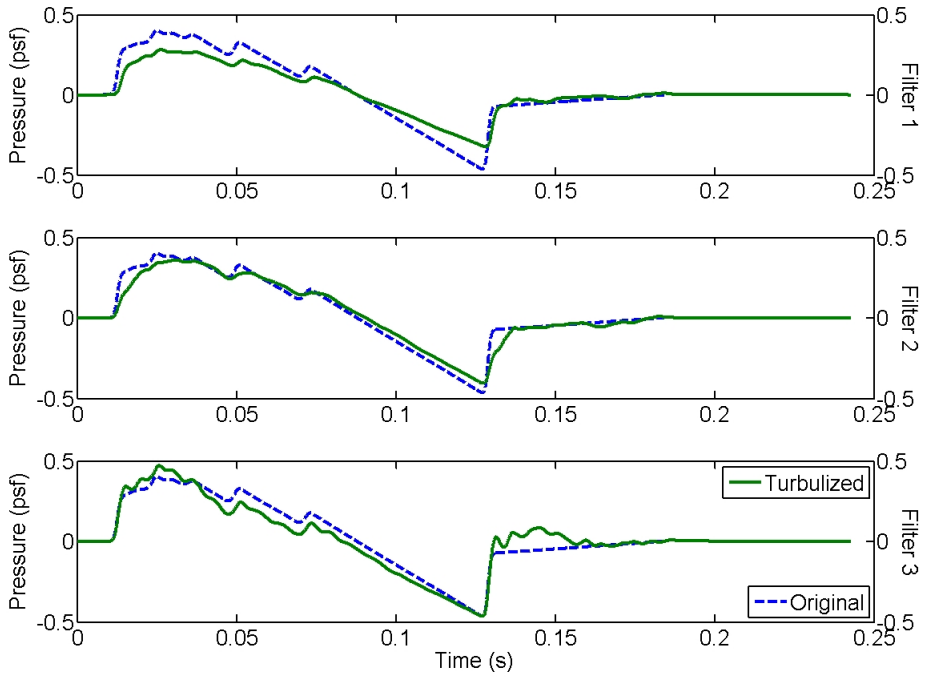
Research on Turbulence and Sonic Booms

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2003-2013



Want to include turbulence in sonic boom signatures for jury tests.





Atmospheric turbulence is likely to affect low-boom signatures such that their loudness levels will vary considerably.

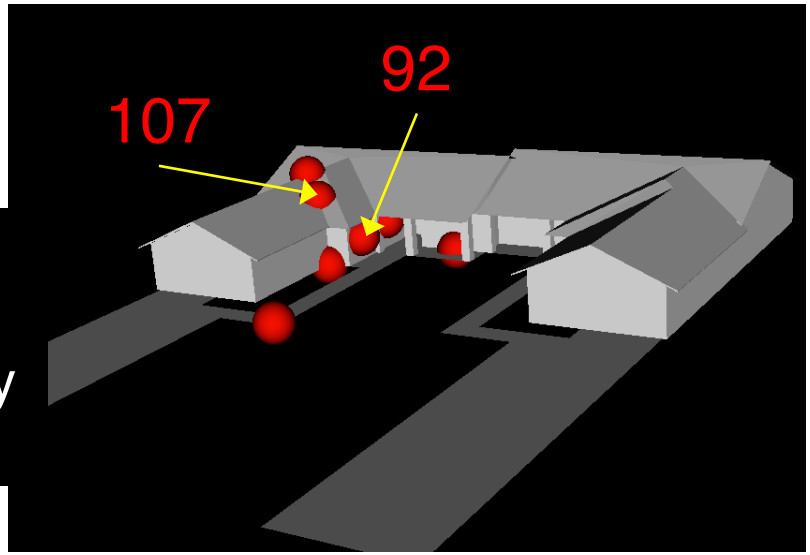
L. Locey and V. Sparrow, "Modeling atmospheric turbulence as a filter for sonic boom propagation," Noise Control Eng. J. **55**(6) 495-503 (2007).

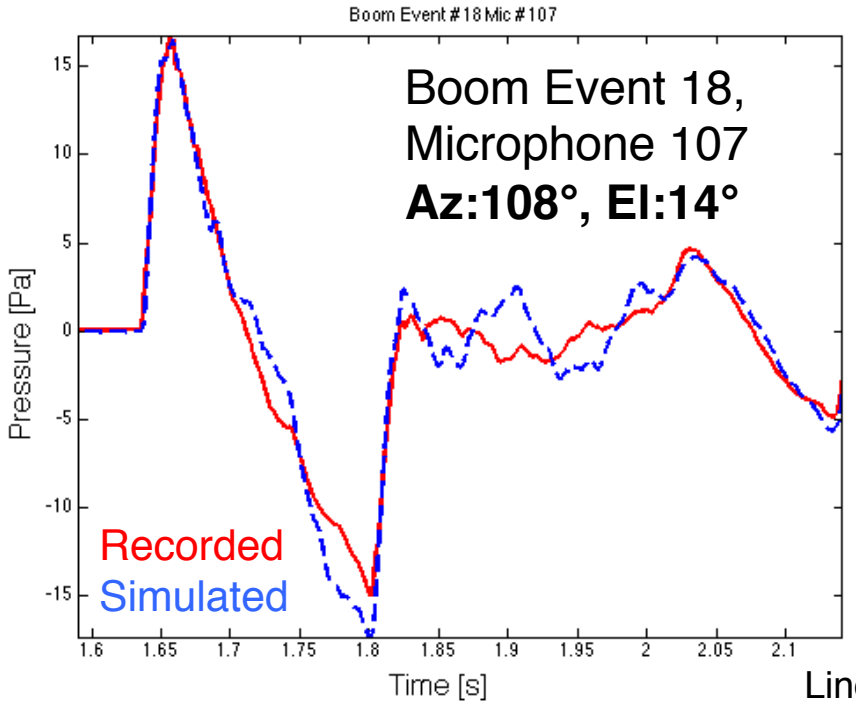
Research on Reflections and Sonic Booms

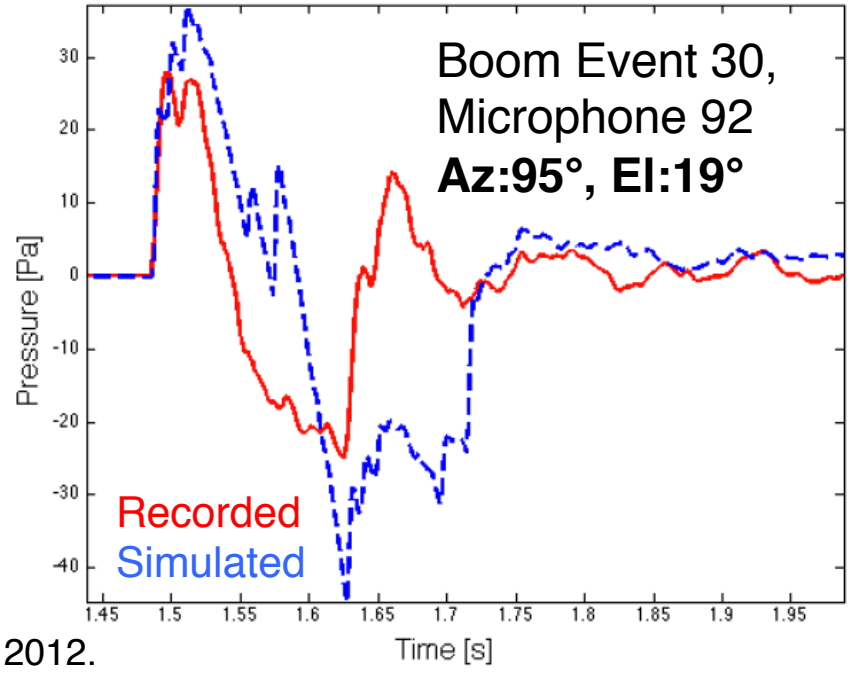
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Want to include building reflections in sonic boom signatures for jury tests.

Built computer model of reflections for realistic geometry, matching NASA measured geometry







Lind, 2012.

Propagation Outcomes

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- Good guidance for FAA and Volpe
- Good inputs for CAEP/WG1/SSTG
- Sonic boom signatures for jury testing
  - See next talk by Prof. P. Davies

Propagation Summary

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10 YEARS
2003-2013

- We are doing a better job on the propagation of noise than we were 10 years ago.
- Future challenges:
  - Realistic atmospheres
  - Integration with other environmental tools, e.g., air quality
  - Integration with aircraft operational tools
  - Supersonic overland flight

Propagation Contributors



- FAA! Thanks for making all this possible.
- Industry Partners: Boeing, Cessna, Gulfstream, Lockheed, Wyle.
- Investigators: Anthony Atchley, Xiao Di, Tom Gabrielson, Kathleen Hodgdon, Kai-Ming Li, Vic Sparrow
- Students: Randy Carbo, Brad Dunkin, BeomSoo Kim, Amanda Lind, Lance Locey, Kieran Poulain, Rachel Romond, Joyce Rosenbaum, Bao Tong
- PARTNER Noise Universities: Penn State, Purdue, GaTech, Univ. of Pennsylvania
- PARTNER Administration: MIT (all, but especially Jennie, Helen, and Bill)
- Very special thanks to:
  - NASA
  - Volpe
  - Penn State Applied Research Laboratory
  - Delta (Denmark)
  - Lou Sutherland

PARTNER RESEARCH, 2003 – 2013

PUBLIC SYMPOSIUM

NOISE

PARTNER COE Project 24: Noise Annoyance Research

(Early Project 2 & 8 Research, Related to Projects 19 & 25)

Presented by: Patricia Davies,
Director, Ray W. Herrick Laboratories,
Professor of Mechanical Engineering, Purdue University, West Lafayette, IN

Opinions, findings, conclusions and recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of PARTNER sponsor organizations.

10th Year Public Symposium
March 1, 2013
Costa Mesa, CA

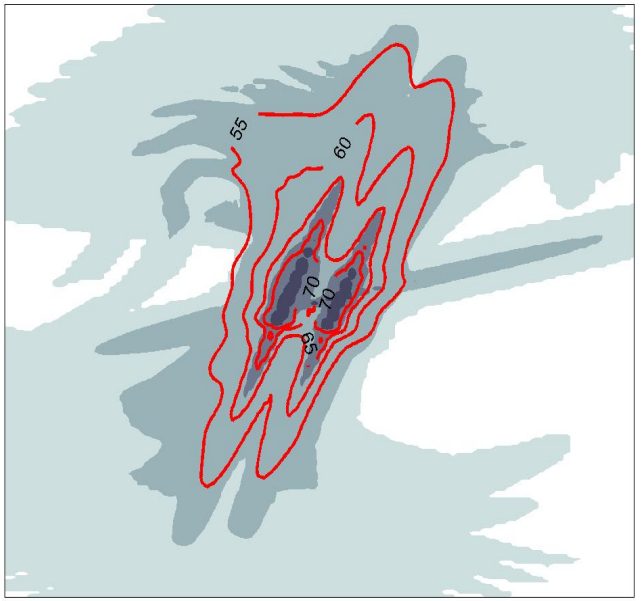
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Partnership for Air Transportation Noise and Emissions Reduction

Motivation

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- Reduce annoyance due to aircraft noise by providing better annoyance prediction tools than are currently available
- Annoyance
  - Potential Long Term Health Issue
  - Quality of Life Issue

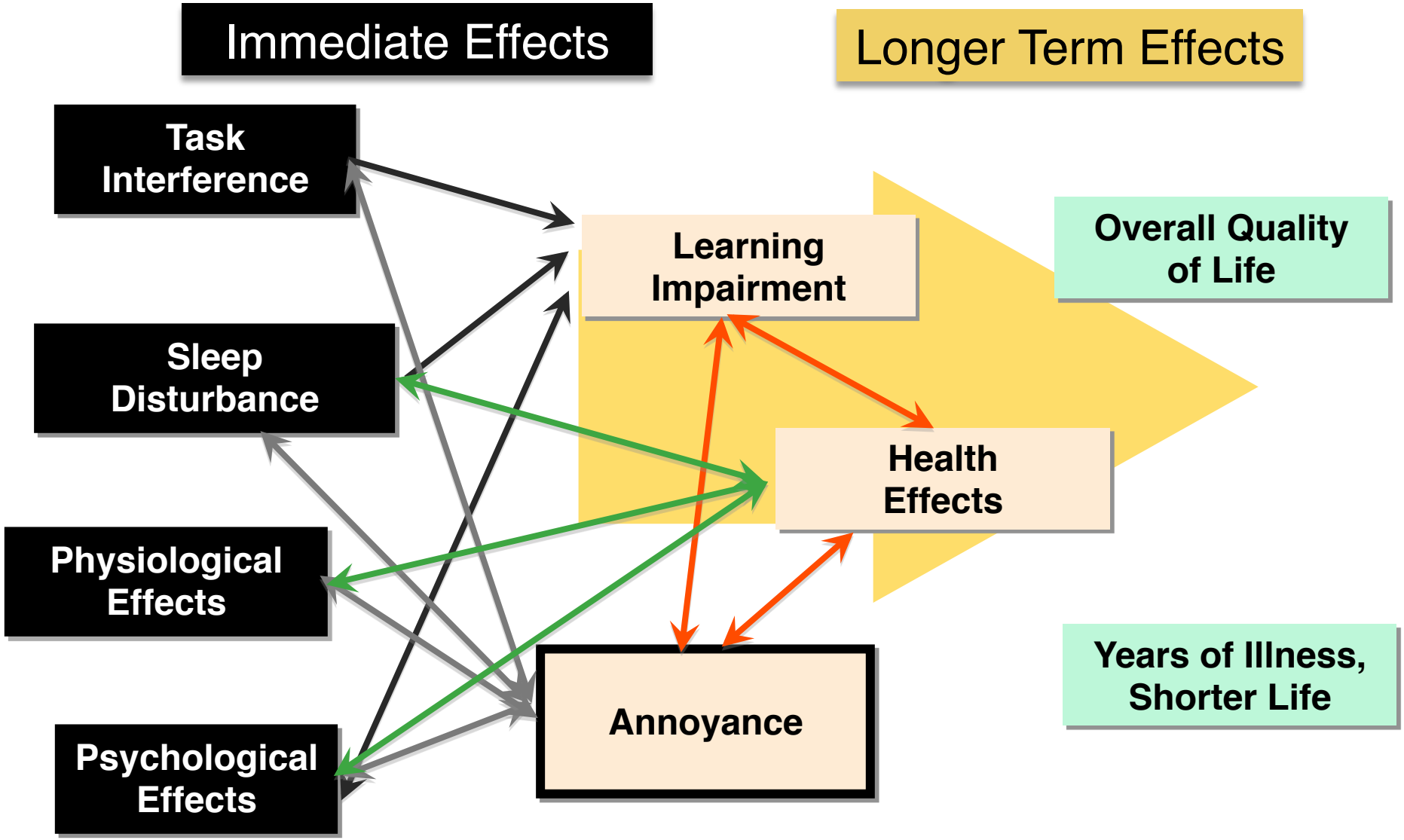
(Burden of disease from environmental noise, Chapter 6, World Health Organization, Europe, 2011)



- IMPROVE
  Understanding → Models → Predictions → Protection

Potential Impact of Noise Exposure

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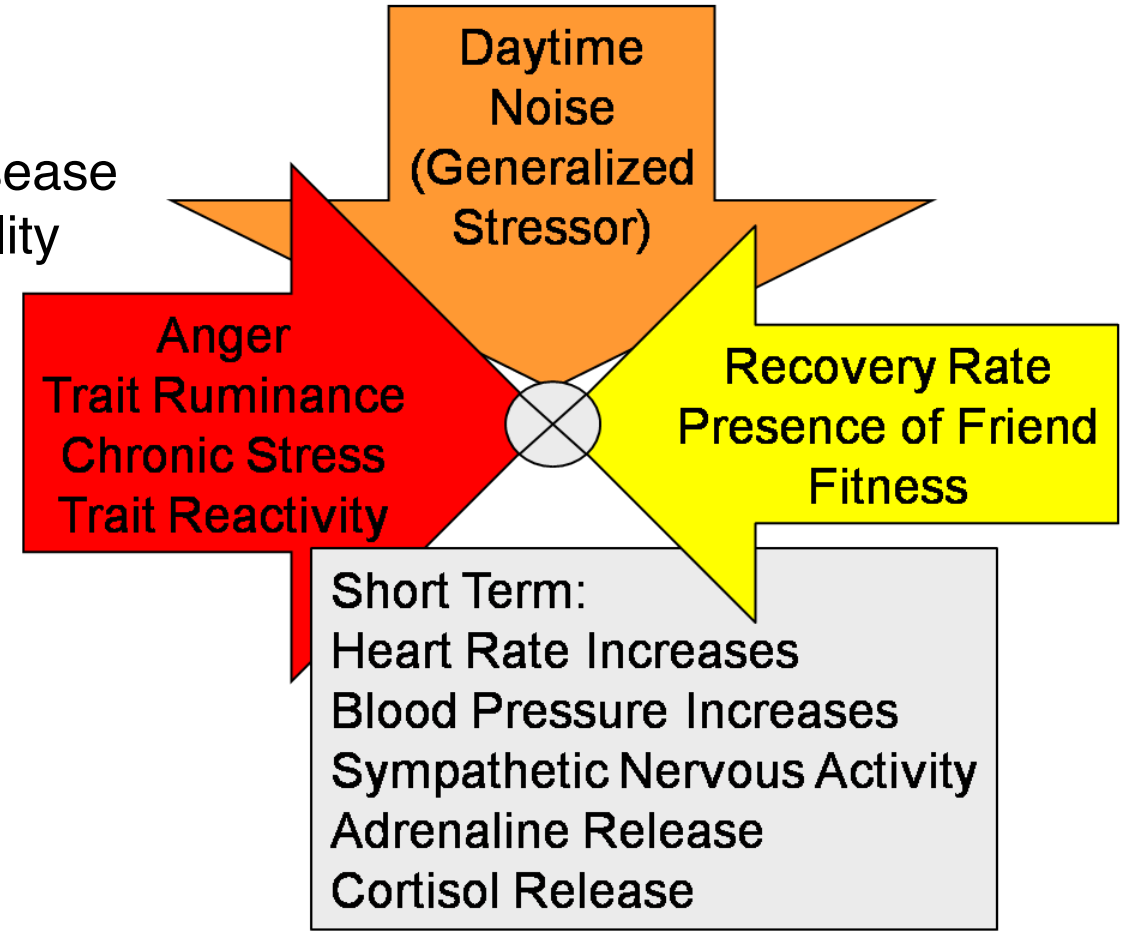
Motivation:
Annoyance & Cardiovascular Health:
Plausible Pathway

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SOUND

→ annoyance (noise)
→ physiological arousal
(stress indicators)
→ (biological) risk factors
→ disease (cardiovascular disease
and hypertension) & mortality

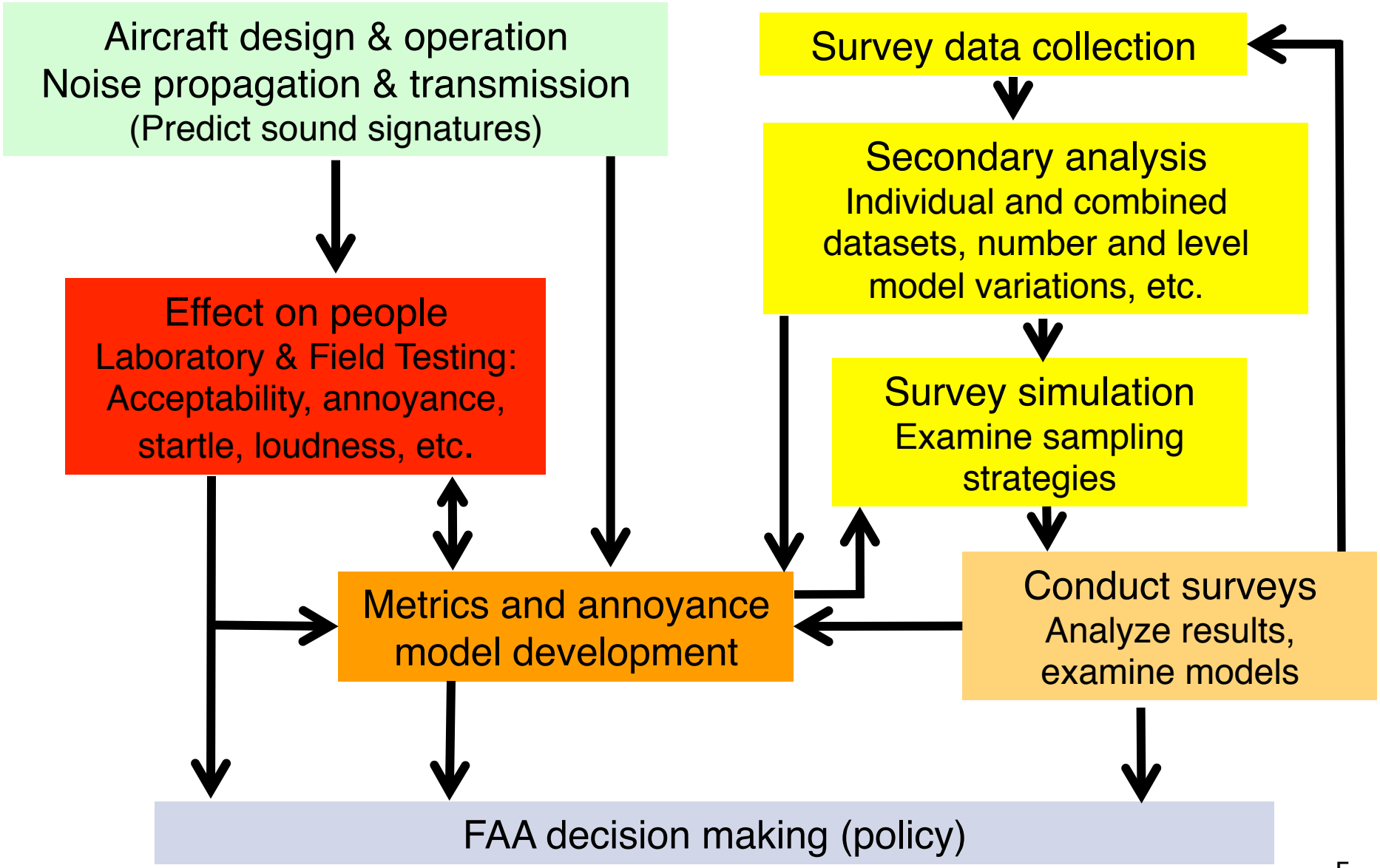
Modifiers of
Annoyance
Reaction



Vulnerable groups:
noise sensitive, older
people, people with
anxiety, ……

Project 24 Challenge: To Develop Better Annoyance Models

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Project 24 Annoyance Research

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Response to Sonic Booms (Enroute noise)

(A) Realism of Playback
(B) Booms Outdoors: Startle & Annoyance Responses
(C) Booms Indoors
(D) Sonic Boom and Subsonic Aircraft Noise Outdoor Simulation

Annoyance around Airports

(E) Sound Quality Issues in Annoyance
(F) Planes, Trains and Automobiles & Sound Meaning
(G) Old Survey Data Reanalysis, Level & Number Models
(H) Survey Simulations

Supersonic Aircraft Enroute Noise Annoyance Research

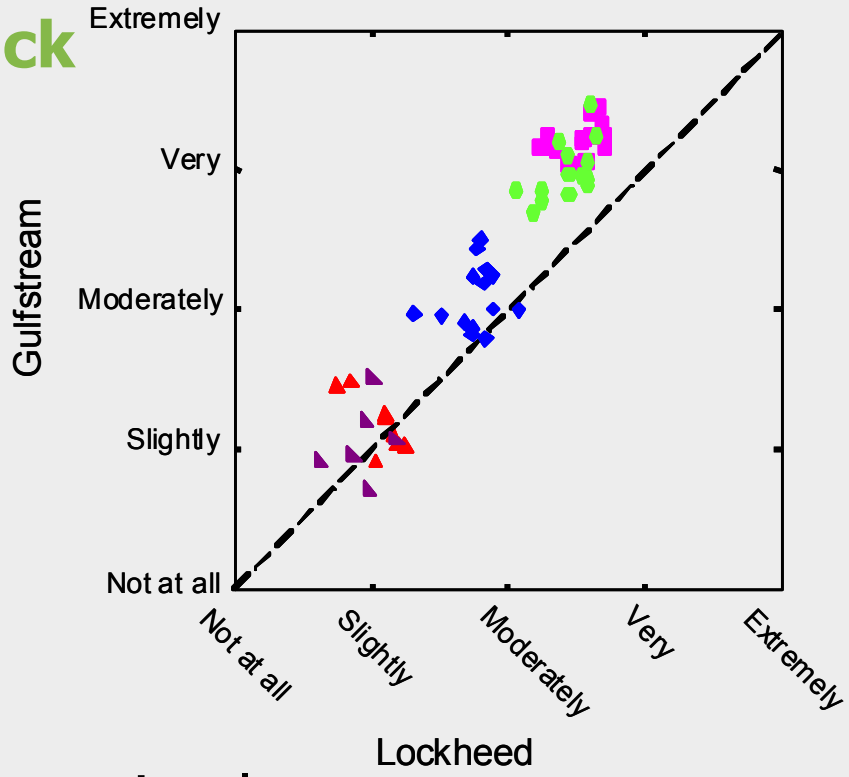
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(A) Realism of Sound Playback

Simulator Comparisons

NASA vs. Gulfstream
Outdoor listening vs. Gulfstream;
Gulfstream vs. Lockheed Martin

High Quality Earphones vs. Gulfstream
(Marshall, Purdue)



Conclusions

Similar results when using different simulators

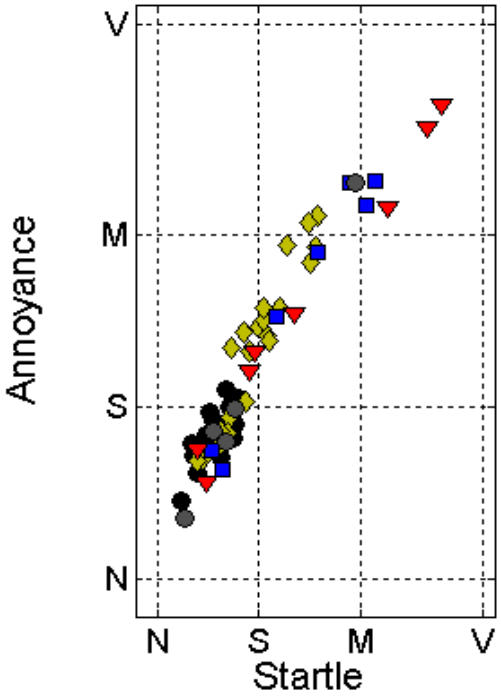
Duration of post-boom noise is important for realism.
Duration(seconds) ■ 3.62 ● 1.62 ◆ 0.72 ▲ 0.29 ◣ 0.22

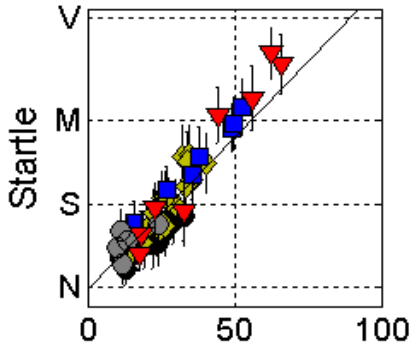
Sullivan, Davies, Hodgdon, Salamone, Pilon. *Noise Control Engineering Journal*, 56(2), March 2008. Realism assessment of sonic boom simulators.

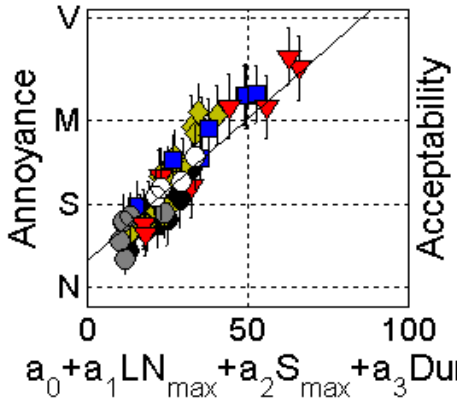
Supersonic Aircraft Enroute Noise Annoyance Research

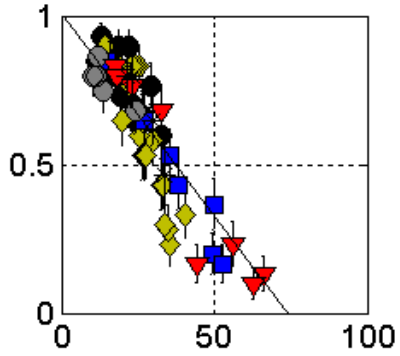
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(B) Booms Outdoors: Startle & Annoyance Modeling









- Booms
- Simulated Booms
- Booms w/echoes
- Boom-like noise
- Blasts
- Door slams

Conclusions

Physiological (difficult to measure) and psychological (straightforward to measure) startle responses consistent and characteristic of an *orientation-type* response.

Psychological responses very repeatable.

Model with 3 Metrics:

Maximum Loudness (Moore & Glasberg Algorithm)
Maximum Rate of Change of Loudness / Sharpness
Duration

predicts annoyance very well.

Supersonic Aircraft Enroute Noise Annoyance Research

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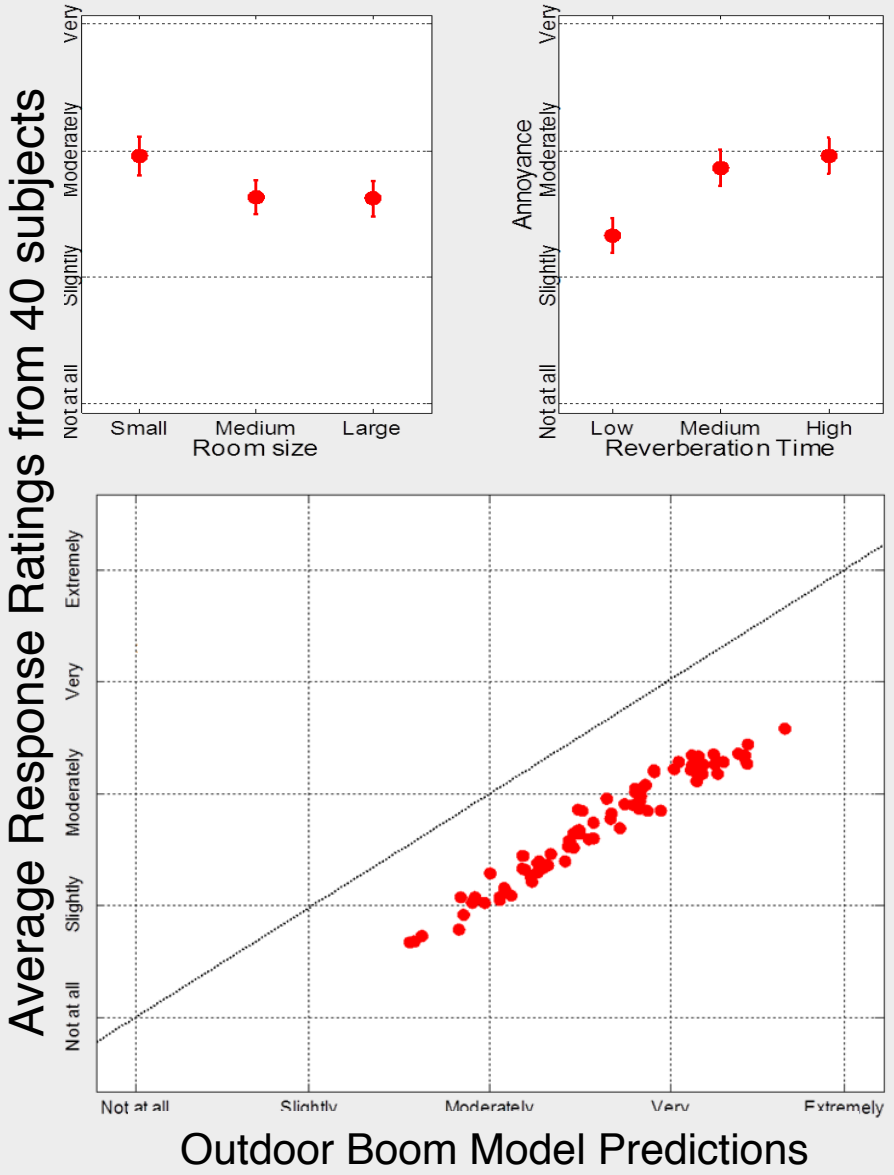
(C) Booms Indoors

Complexities in the indoor environment:
Echoes, room shape, room sound absorption, rattle
House-boom interaction and transmission complex

Developed a simplified simulation program that includes directional effects of sounds reaching the listener.

Findings
Outdoor boom model predicted indoor boom annoyance rating trends very well.

Duration was found to be important indoors, even though all stimuli were simulated booms.



Supersonic Aircraft Enroute Noise Annoyance Research

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(D) Sonic Boom and Subsonic Aircraft Noise Outdoor Noise Simulation

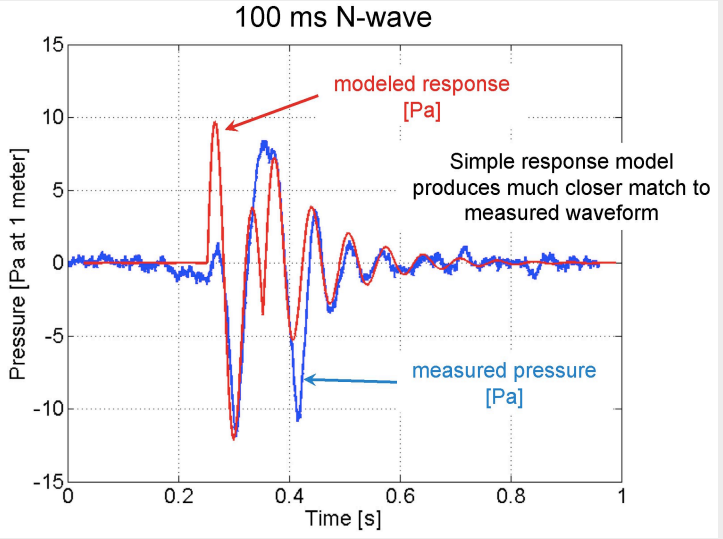
Goals

To examine the feasibility of developing a portable simulator/trailer that could be placed near homes in a community to produce aircraft noise

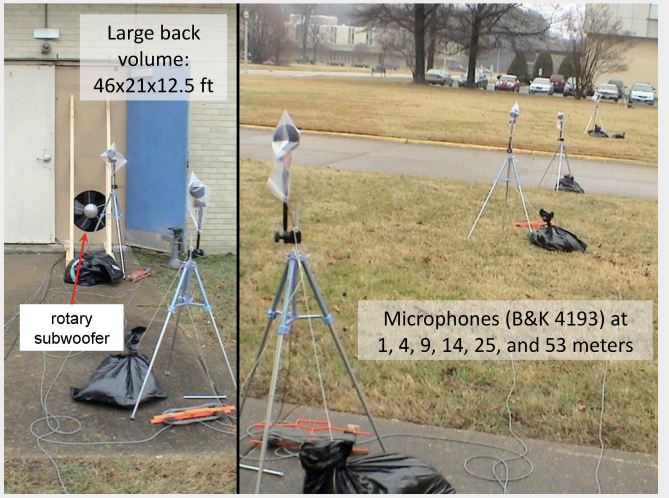
Laboratory → **Controlled Field Tests** → Community Surveys with Aircraft

Examined different technology for reproducing the sounds.

Recommended looking at electrodynamic (outdoor concert like) systems as a future project.



rotary subwoofer testing



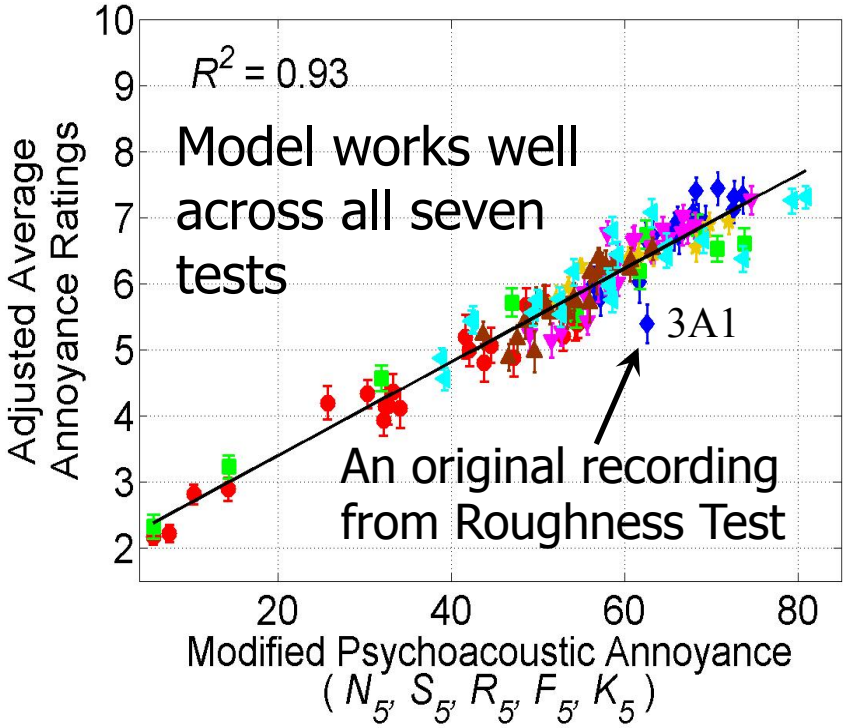
Annoyance Around Airports Research

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(E) Sound Quality Issues in Annoyance

7 tests to look at influence of different sound attributes on perception of aircraft noise

Loudness
Sharpness
(High vs Low Frequency Energy)
Tonality
(discernable pitch)
Roughness
Fluctuation



	PA_{mod}	*PA*	*EPNL*	*Revised JNM*	*JNM*	*SELA*
R^2	**0.93**	0.86	0.88	0.89	0.86	0.88

Performance of different metrics in explaining responses R^2 0:poor; 1:perfect

Annoyance Around Airports Research

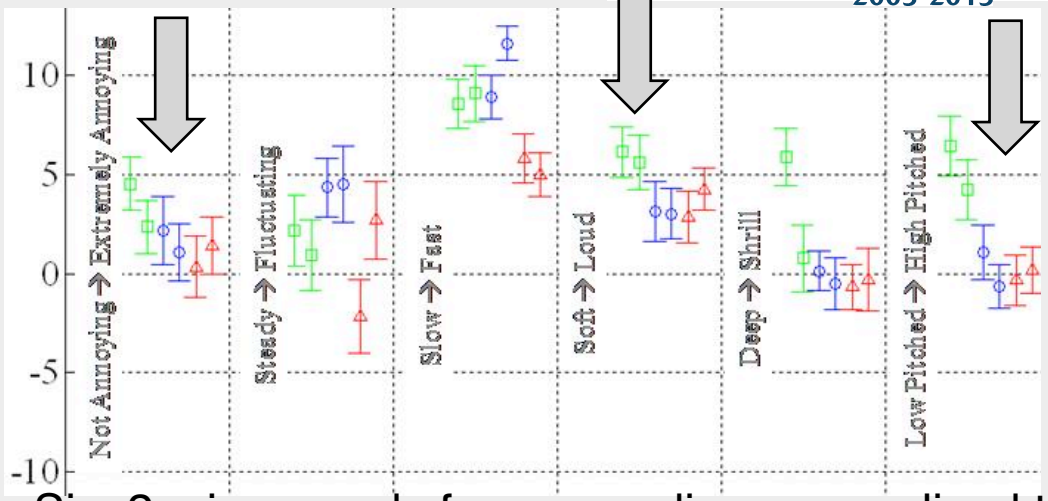
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(F) Planes, Trains and Automobiles & Sound Meaning

Response to Aircraft, Trains and Road Traffic Different? Or is Day Night Level the problem?

Small study looking at how do people's responses change if they don't know the source of the sound?

Recording →
Neutralizing Source Information
→Modified Sounds



Six, 2 min. sounds from recordings normalized to Same average A-weighted Sound Pressure Level,

Results:
Loudness ratings unchanged by modification

Neutralized sounds judged as "vaguer", "slower" and slightly more annoying, irritating and unpleasant.

Harder to neutralize aircraft and some road noise

Annoyance Around Airports Research

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2003-2013

(G) Old Survey Data Reanalysis, Level & Number Models

- Difficult to obtain old data, sensitivities in sharing data
  - Many thanks to Jim Fields, Larry Finegold and the 1999 UK Sleep Study Team & UK CAA for sharing data that they had collected.
- Important data in archived surveys often missing and difficult to reproduce from other data
  - Operations, aircraft, community information
  - A limited number of metrics
  - Difficult to use to explore use of different models
  - Site level vs. individual level noise exposure reporting

Annoyance Around Airports Research

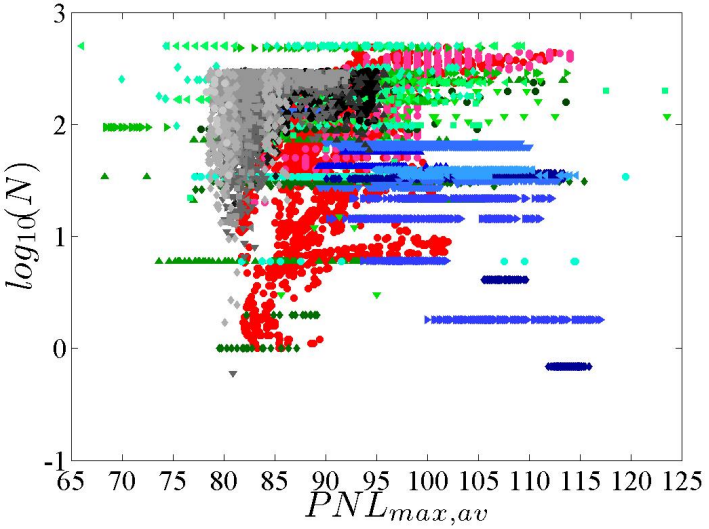
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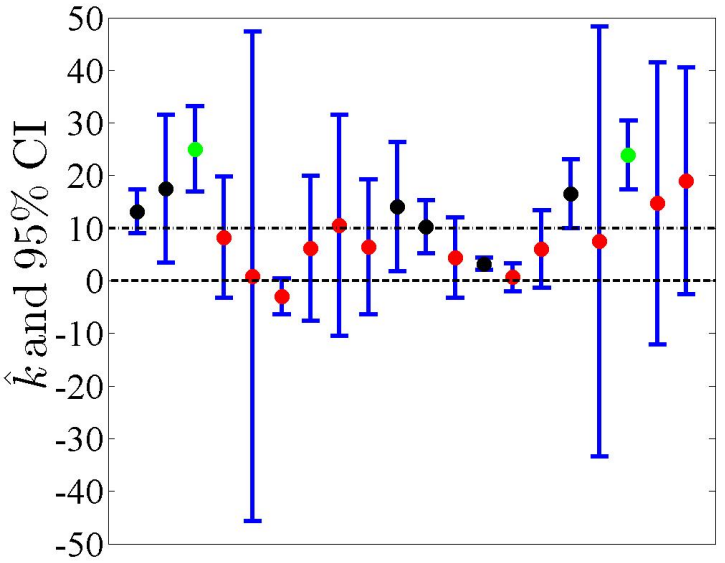
(G) Old Survey Data Re-Analysis, Level & Number Models

Reanalysis of data looking at Noise Level & Number of Events Models

- 2.2 GB data from 9 survey sets transcribed from 18,400 slides of microfiche
- UK ANASE Study Data (extracted from report tables) added to this
- 20,829 samples, 1967 to 2006
- Transformed data to have unified metric and annoyance scales
- Examined individual surveys and airports, and combinations of data sets

GOAL: to determine if number of events was more (k>10, or less, k<10) important relative to average level of events than in the *DNL* metric (k=10).





Annoyance Around Airports Research

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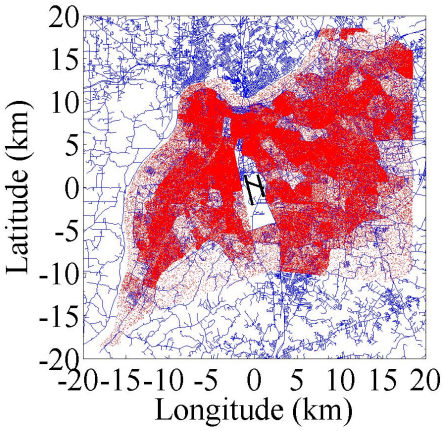
(H) Survey Simulations

Household simulation based on Census Data, includes non-acoustic and acoustic data.

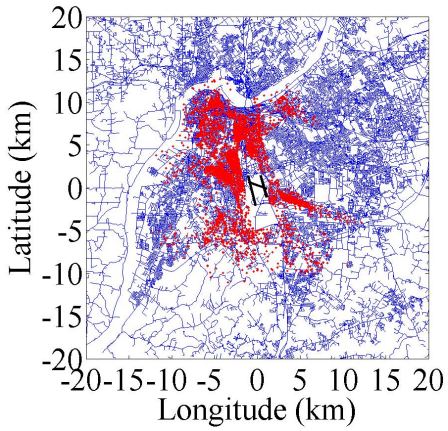
3 US Airports used as sample survey locations

Used simulation tool to look at how, on average, sampling strategies impact Noise Level & Number of Events Model Estimates

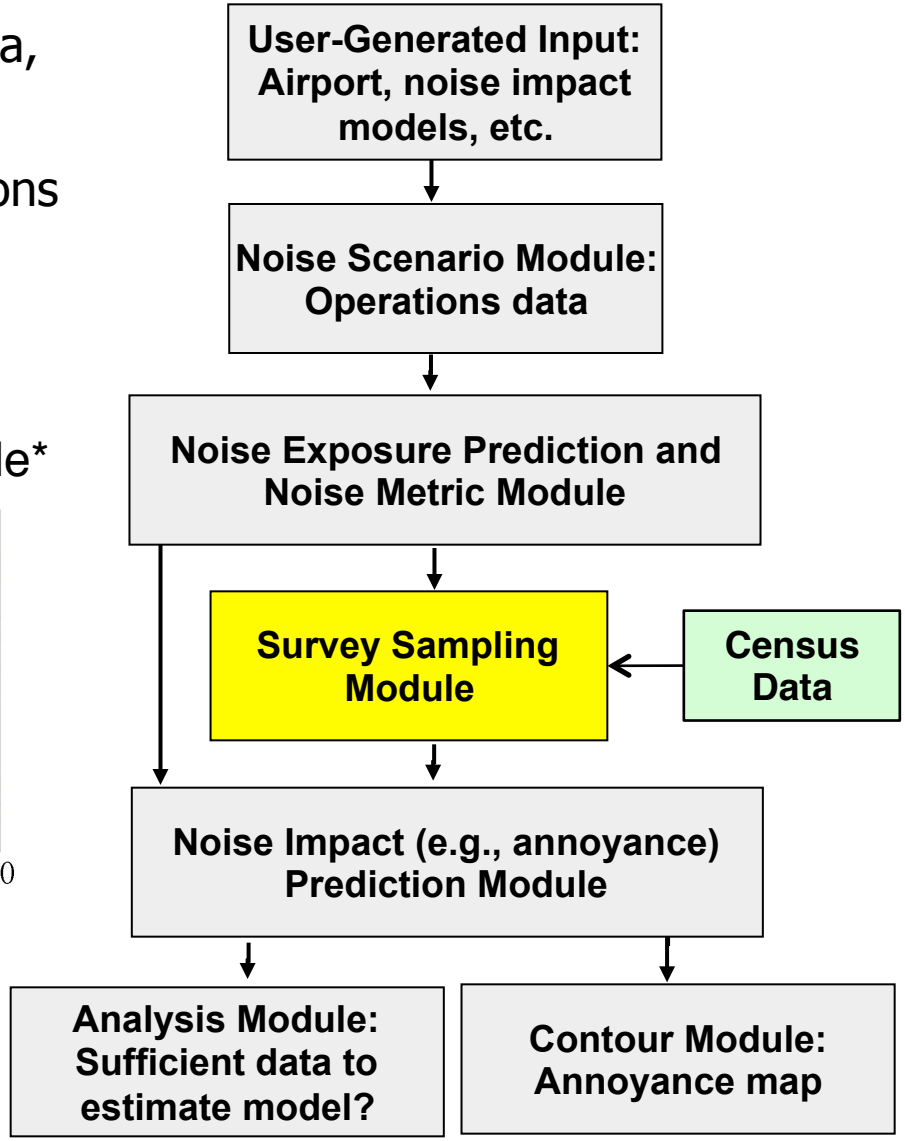
All households



Typical 6000 sample*



Findings: Poor sampling can lead to high variation in estimates → inaccurate models → difficult to draw conclusions on utility of different modeling approaches



Outcomes

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10 YEARS
2003-2013

Improved Noise Annoyance Models Developed

- A model for annoyance caused by transient environmental noise including sonic booms
- A model for annoyance caused by aircraft operations near airports
- Both models utilize loudness models for capturing people's perception of the level of a sound
- Both models include quantification of other sound attributes

A Survey Simulation Tool Developed

- Can use it to examine the ability to validate annoyance models given particular community sampling strategies.
- Can be used to improve survey design
- Results in the collection of more useful data

Report of Project 19: A Review of Literature Related to Potential Health Effects of Aircraft Noise.

- Examined the literature for plausible pathways to cardiovascular disease from aircraft noise exposure.
- Annoyance and sleep disturbance both plausible pathways.

Interfaces and Communications

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10 YEARS
2003-2013

Industry & Government

- Gulfstream, Boeing, Lockheed Martin, Cessna, Bombardier
- HMMH, Wyle
- Volpe Center
- NASA Langley & Dryden

External to PARTNER

- 23 Internoise, Noise-Con, & ICBEN Papers covering all projects.
- 3 Noise Control Engineering Papers, 6 additional journal papers planned and in preparation.

Within PARTNER

- Researchers involved in PARTNER Projects 1, 2, 8, 19, 24, 25

Reports/Theses:

- 3 MS Theses, 2 Ph.D. Theses, (+1 Ph.D. for Project 25 Research)
- 3 PARTNER REPORTS (More to follow)

Summary & Looking Forward

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10 YEARS
2003-2013

Demonstrated that there is scope for improvements to:

- currently used aircraft noise annoyance models
- how data is collected and archived in surveys

Next address transition from predicting single event responses to predicting cumulative effects of aircraft noise in realistic environments

Upcoming

- advances in the speed and accuracy of sound simulations will, in the next few years, open up the possibility of *easily* listening to what things will sound like (new runway, new fleet, changing mix of aircraft, new house near an airport…..)
- advances in technology for gathering of response data

Annoyance modeling efforts should take advantage of these changes in technology

- Collaborations on future annoyance survey designs
- Analysis of subsequent data

Contributors



- Mehmet Marsan, Natalia Sizov, Laurette Fisher (retired), FAA

- Richard Widdle, post doc, Purdue
- Shashikant More, Ph. D., Purdue
- Andrew Marshall, MSME Thesis & Ph. D., Purdue
- Sarah McGuire, MS/Ph.D., Purdue (Project 24 & Project 25)
- Chloe Giacomoni, MS, Purdue
- Kevin Foertsch, MS, Purdue

- Vic Sparrow, Kathleen Hodgdon, Steve Garrett, Penn State
- Patricia Davies, Hong Tan, George Chiu (Engineering)
  Shirley Riedtyk, Michael Heinz, Robert Proctor, Beth Strickland, (Health and Human Sciences), Gary Eiff (Aviation Technology), Purdue University.

- Robbie Cowart, Joe Salamone, Joe Gavin, Gulfstream
- Anthony Pilon, Lockheed Martin
- Brenda Sullivan, Kevin Shepherd, Jake Klos, Alexandra Loubeau, NASA Langley, Ed Haering NASA Dryden
- Ken Plotkin, Wyle; Nick Miller, HMMH.
- Eric Boeker and Aaron Hastings, Volpe Center

- Jim Fields & Larry Finegold, Consultants
- Ian Flindell & 1999 UK Sleep Study Team, Peter Havelock UK Civil Aviation Authority

PARTNER RESEARCH, 2003 – 2013

PUBLIC SYMPOSIUM

NOISE

Research on the Effects of Aircraft Noise on Sleep

Presented by: Mathias Basner, MD, PhD, MSc, University of Pennsylvania

Opinions, findings, conclusions and recommendations expressed in this material are those of the author(s)
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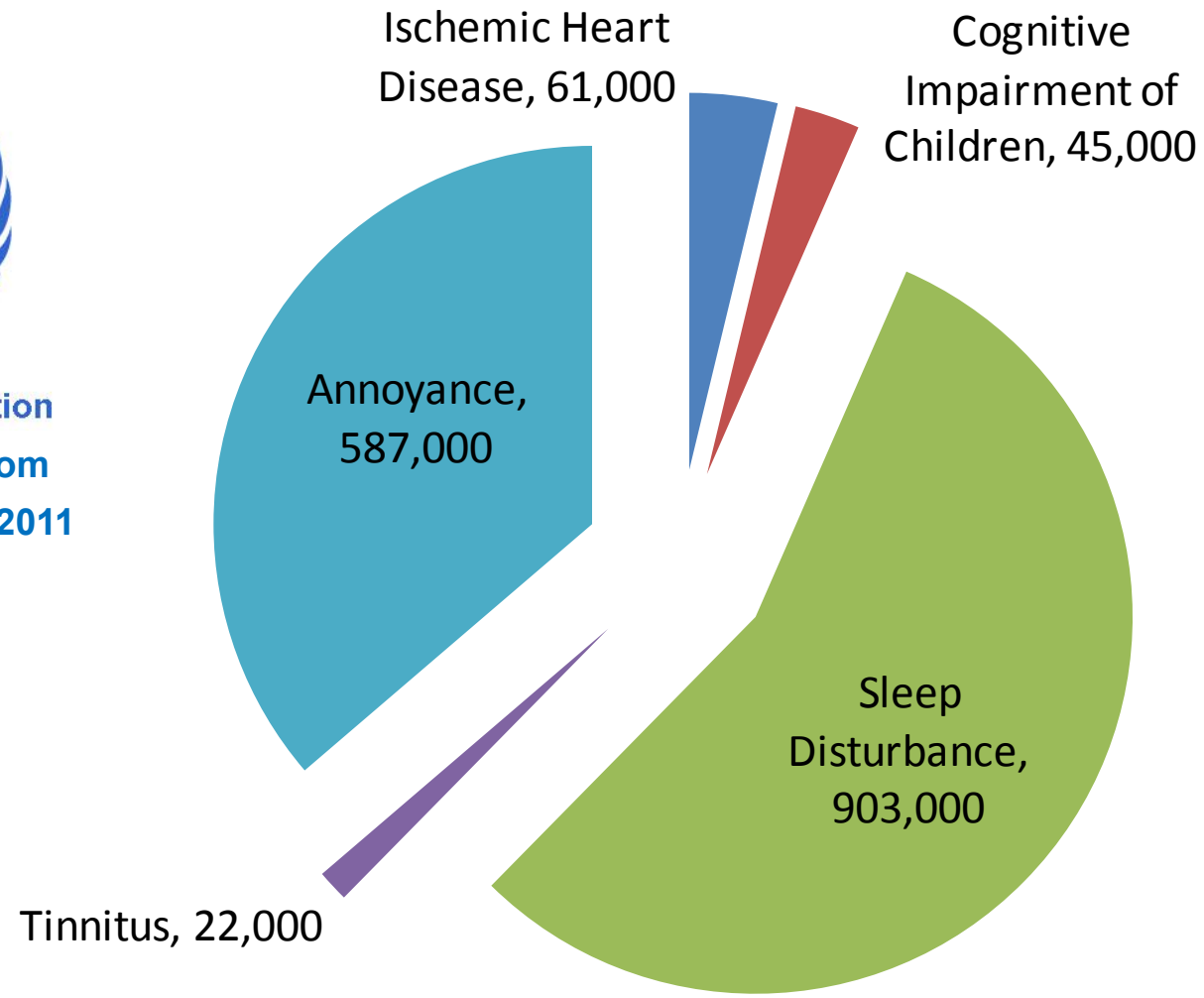
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Costa Mesa, CA

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Partnership for Air Transportation Noise and Emissions Reduction

Motivation

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World Health Organization
Burden of Disease from
Environmental Noise, 2011



According to the World Health Organization, ca. 900,000 healthy life years are lost annually in the EU due to sleep disturbance induced by environmental noise.

Challenge

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10 YEARS
2003-2013

- Aircraft noise disturbs sleep, interferes with recuperation and may contribute to long-term health consequences.
- Air traffic volume has increased over the past 30 years, outweighing much of the success in noise emission reductions of individual aircraft, and decreasing noise-free intervals between events.
- The last U.S. study on the effects of aircraft noise on sleep was performed more than 15 years ago and used inadequate methodology.
- Up-to-date exposure-response relationships on the effects of aircraft noise on sleep are critically needed to assess the validity of current noise policy and to better mitigate the effects of aircraft noise on sleep and health.

Research

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10 YEARS
2003-2013

Objective 1

- Propose an optimal study design for a US field study on the effects of aircraft noise on sleep that is based on current scientific knowledge in both the noise effects research and the sleep research area.

Objective 2

- Develop and validate models that can predict changes in total sleep structure based on traffic volume and patterns.
- Generate contour maps for airports based on noise effects (e.g., awakenings) in contrast to contour maps based on noise exposure (e.g., L_{DN}).

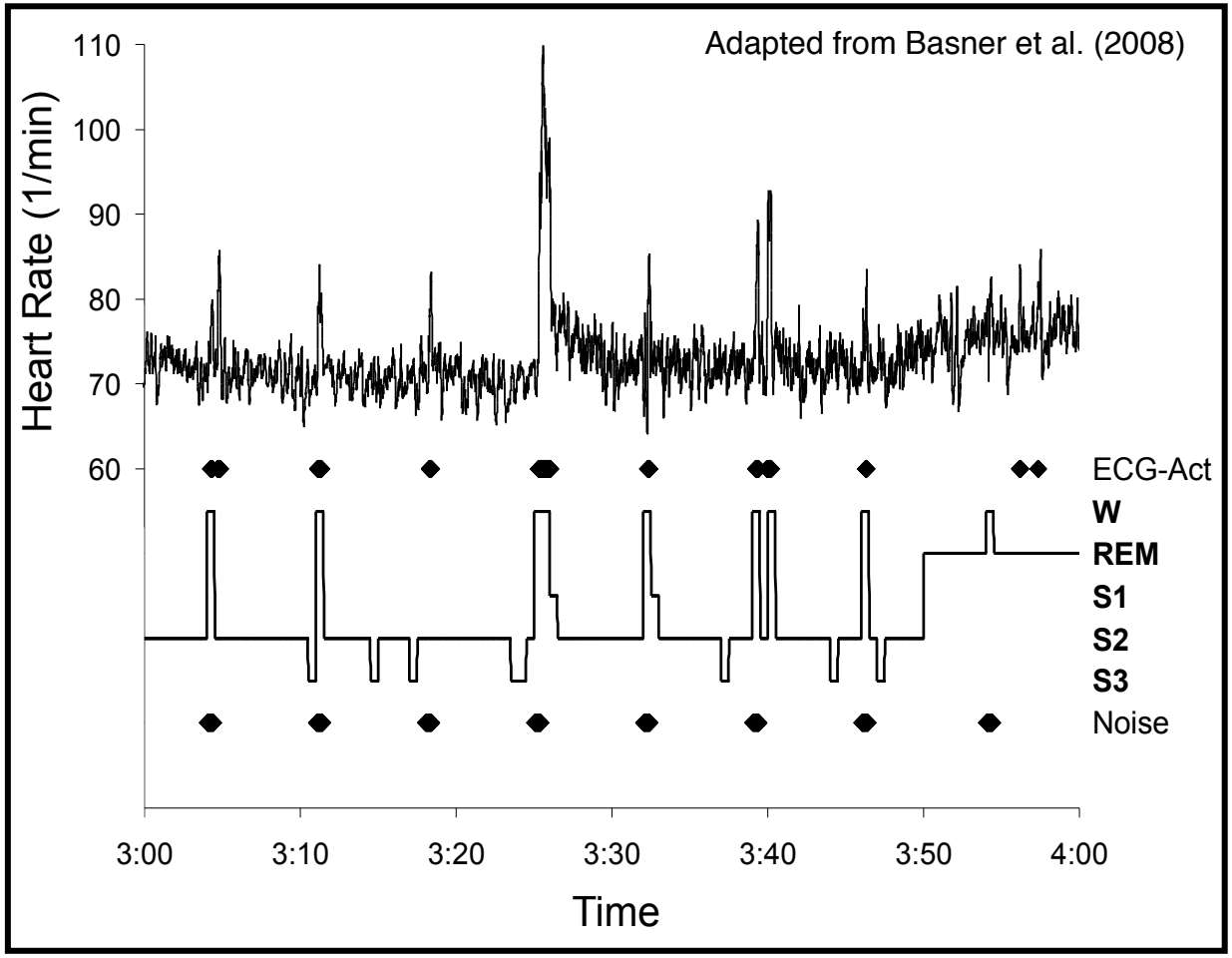
Outcomes Objective 1

PARTNER
10 YEARS
2003-2013

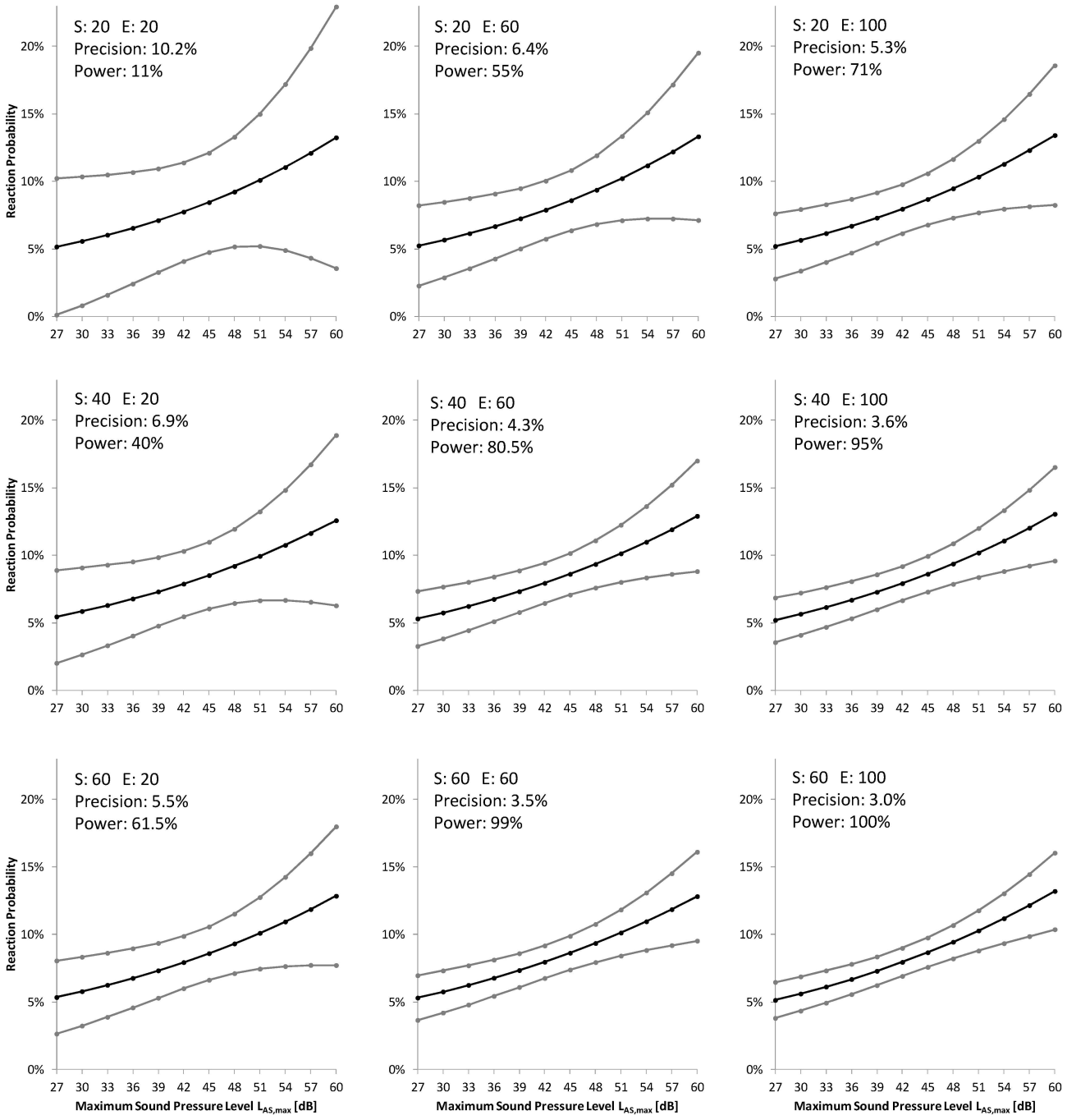
We recommend to use actigraphy plus electrocardiography (ECG) to cost-effectively investigate representative population samples.

Advantages of ECG algorithm to detect awakenings:

- Low cost but meaningful results
- Self-administration of electrodes possible
- Automatic analysis without inter-rater variability
- Robust signal
- ECG habituates to a lesser degree than EEG



Basner, M. et al: Physiological Measurement 29(9), 1089-1103, 2008
Basner, M. et al., Noise & Health, 14(61): 321-329, 2012



PARTNER
10 YEARS
2003-2013

Outcomes Objective 1

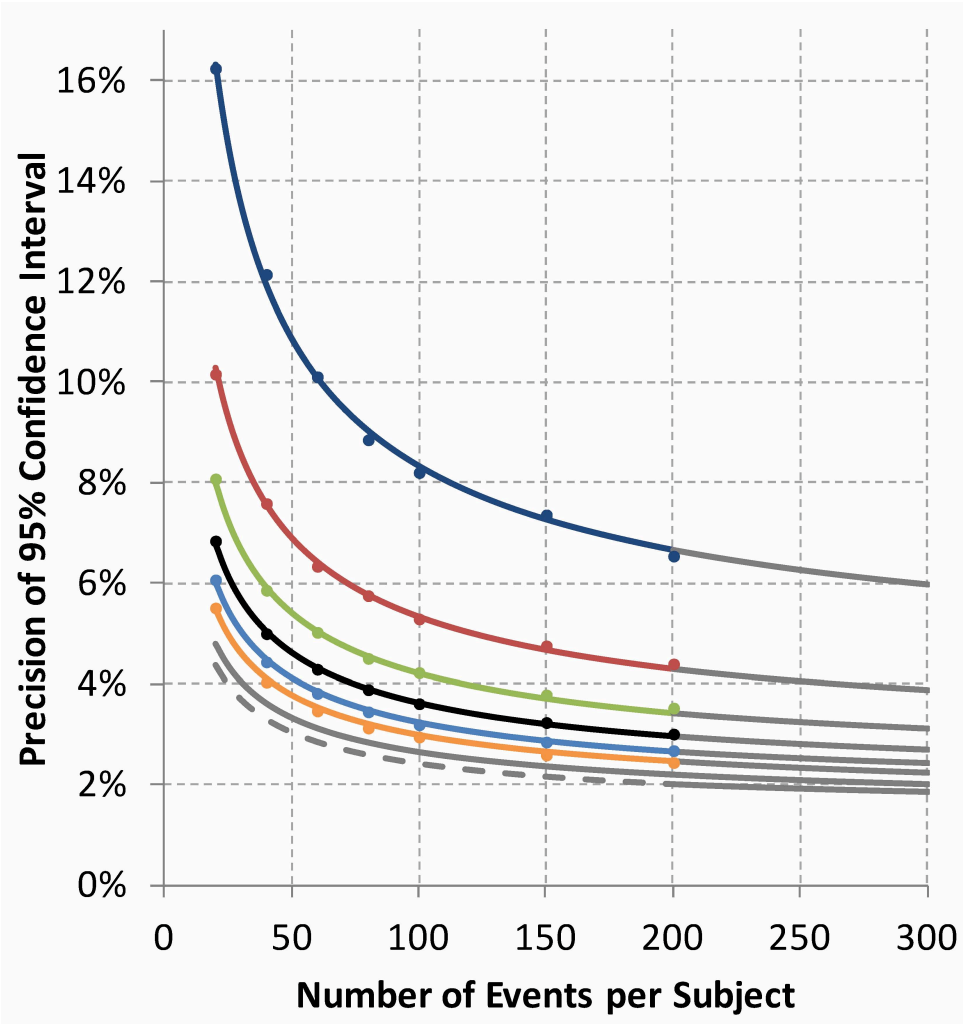
Precision of exposure-response relationship based on number of subjects and number of noise events per subject.

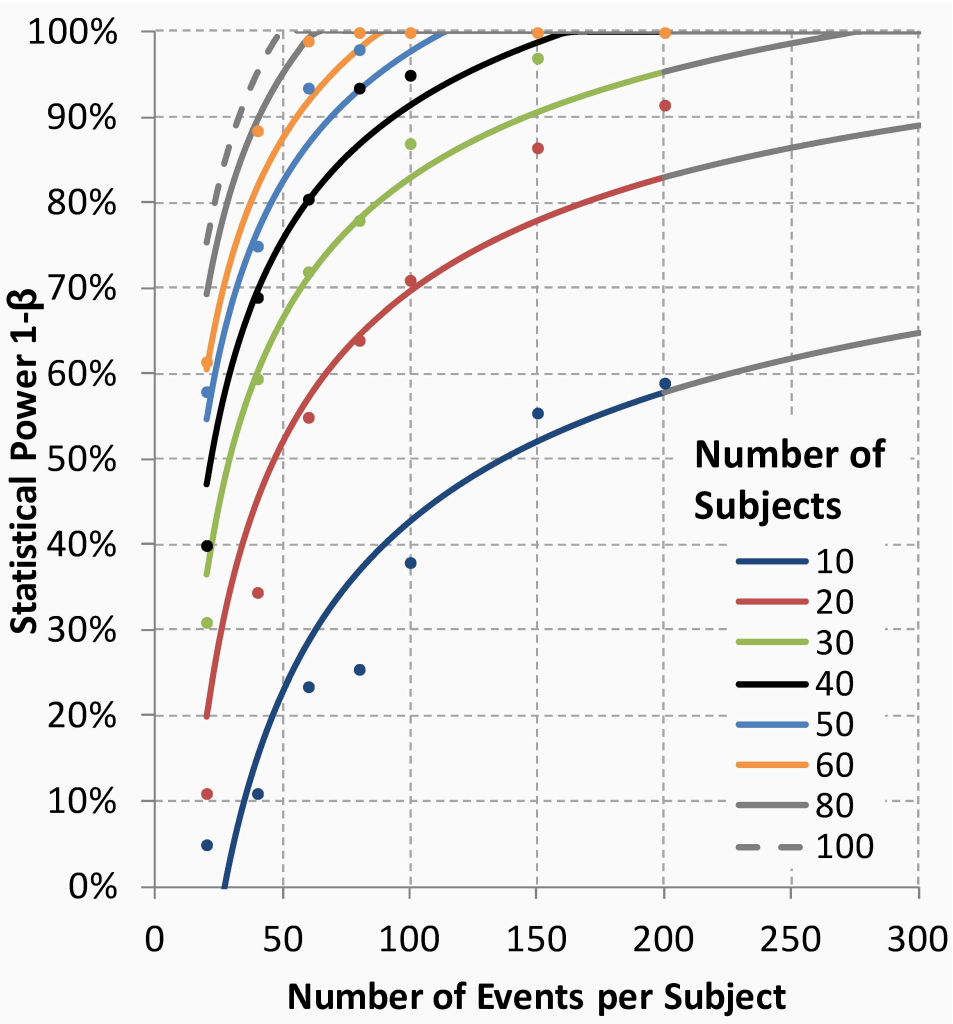
Basner, M., Brink, M., Applied Acoustics, 74(6): 812-817, 2013.

Outcomes Objective 1

PARTNER
10 YEARS
2003-2013

Sample size requirements for an aircraft noise effects field study.



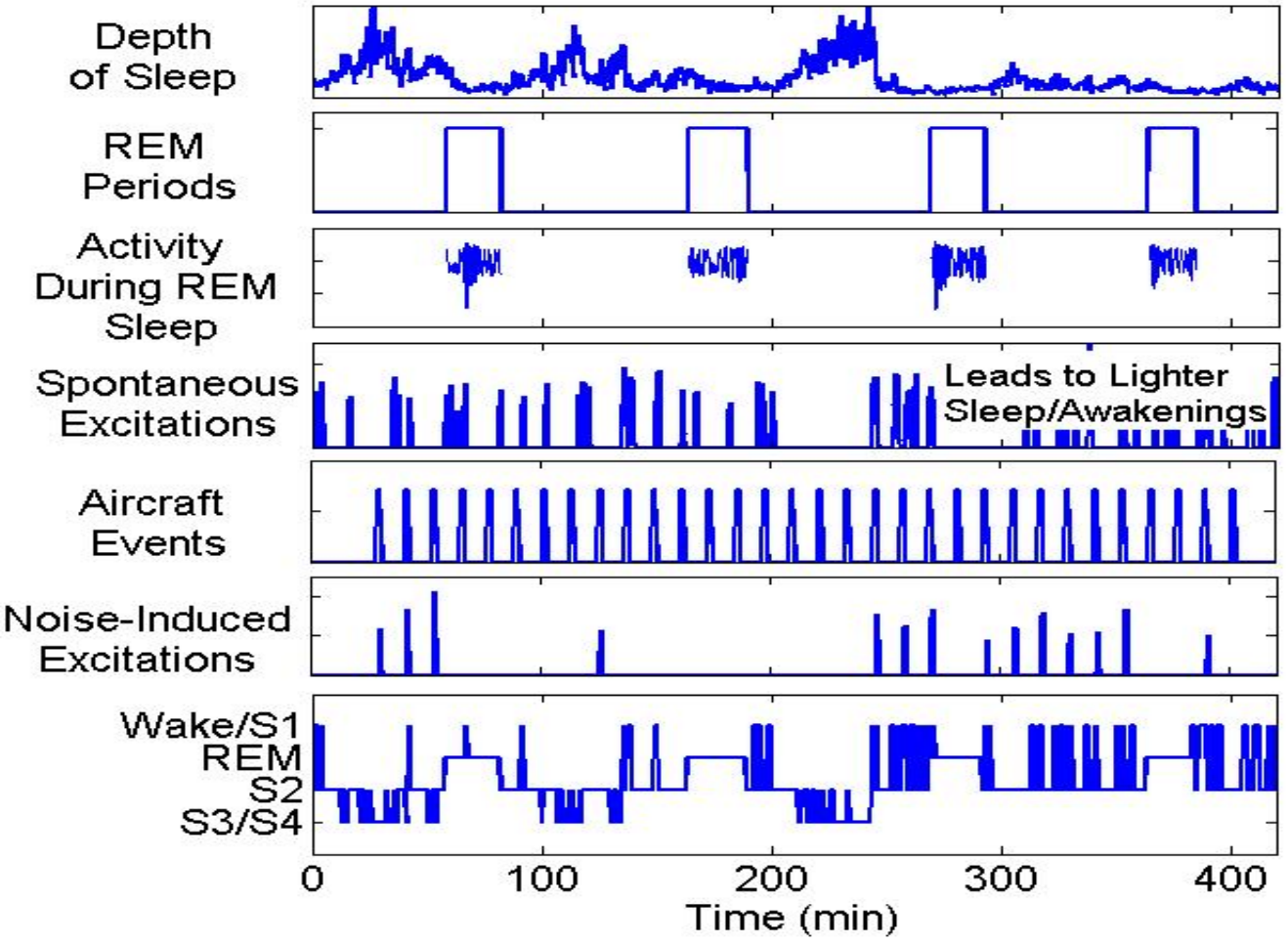


Basner, M., Brink, M.: Sample size estimation for field studies on the effects of aircraft noise on sleep. Applied Acoustics, 74(6): 812-817, 2013.

Outcomes Objective 2

PARTNER
10 YEARS
2003-2013

We developed a model that can be used to predict changes in sleep structure due to aircraft noise exposure.

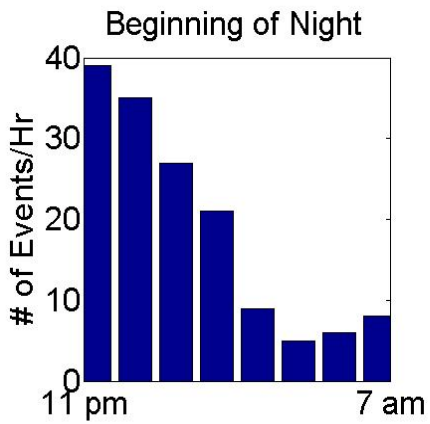


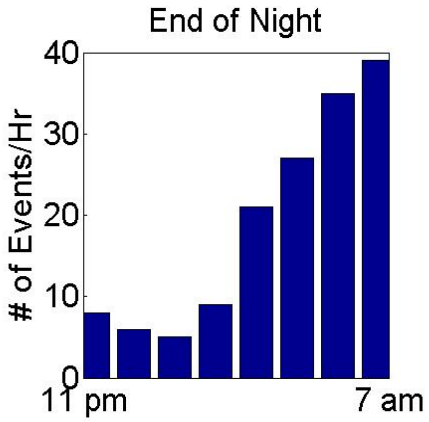
Model based on Massaquoi, S.G., McCarley, R. W. Journal of Sleep Research, 1: 138-143, 1992.

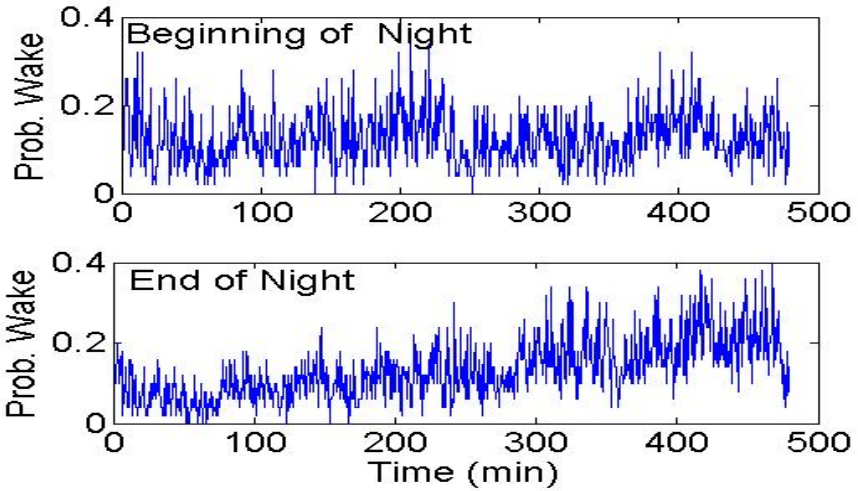
Outcomes Objective 2

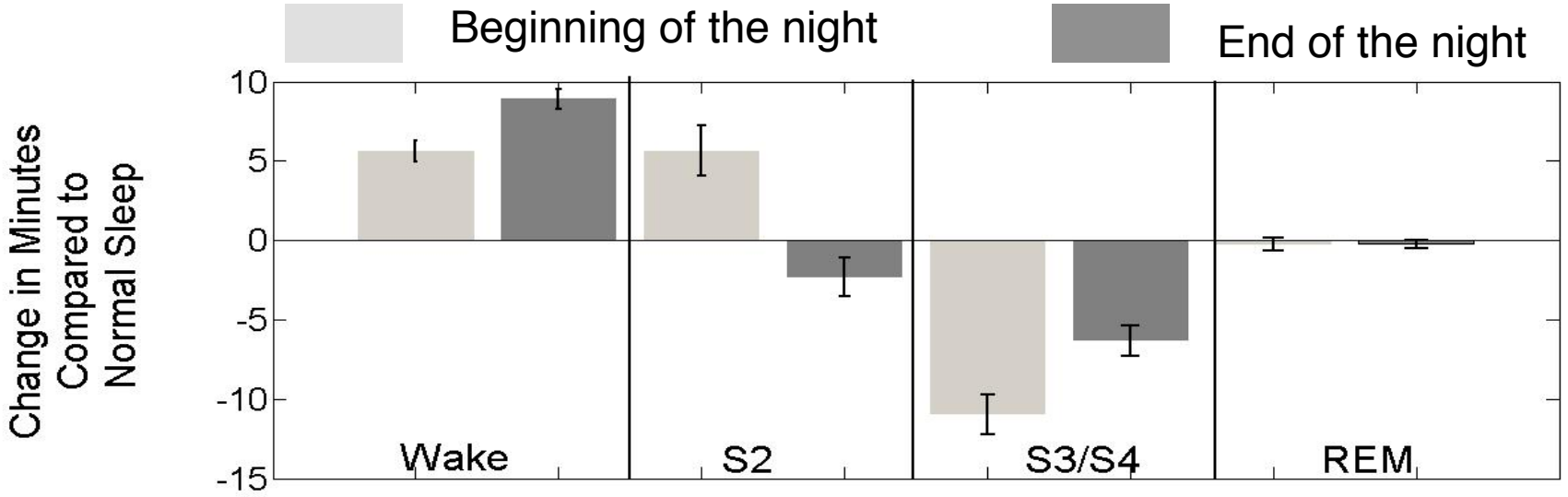
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2003-2013

Examined sleep structure changes for different traffic scenarios







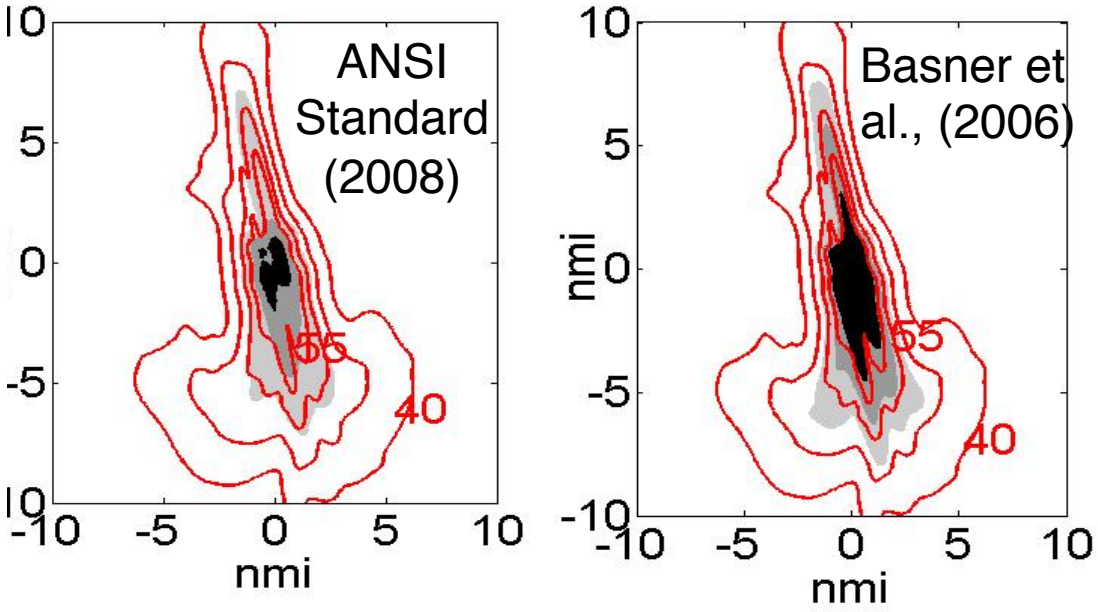


Outcomes Objective 2

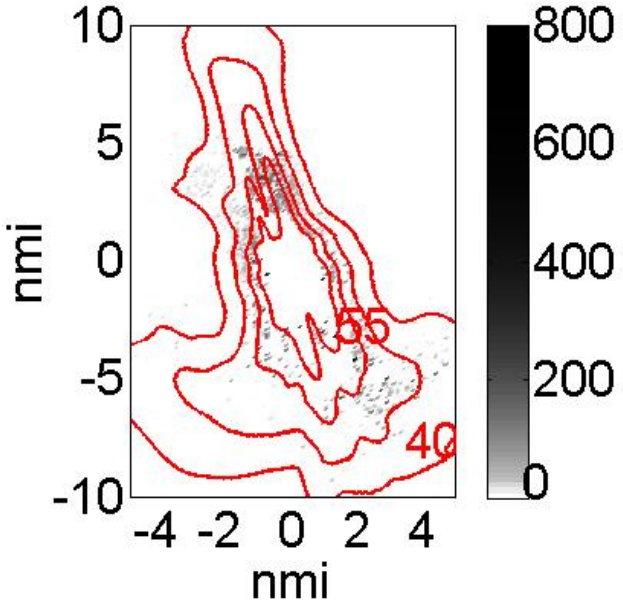
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- Created community impact contours based on awakenings.
- Compared existing sleep models.
- Evaluated potential number of people impacted.

Percent Awakened at Least Once

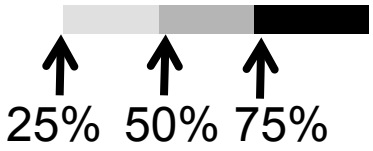


Number Awakened at Least Once



Red Contours: L_{night}

Transitions:



Interfaces and Communications

PARTNER
10 YEARS
2003-2013

- External
  - German Aerospace Center (DLR)
- Within PARTNER
  - Project 24
- Publications
  - Critical appraisal of methods for the assessment of noise effects on sleep. Noise & Health, 14(61): 321-329, 2012.
  - Sample size estimation for field studies on the effects of aircraft noise on sleep. Appl.Acoust., 74(6): 812-817, 2013.
  - Report PARTNER-COE-2012-003
- Presentations
  - Internoise 2012

Summary

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10 YEARS
2003-2013

- Sleep disturbance is considered the most deleterious effect of aircraft noise on humans, and continuous growth of air traffic will only be possible if the effects of aircraft noise on sleep are mitigated.
- We suggest to perform large-scale, methodologically sound, yet affordable field studies on the effects of aircraft noise on sleep in representative population samples and reflecting the variability in air traffic across U.S. airports.
- We also suggest to further improve models for the prediction of aircraft noise effects on sleep that reflect complex traffic scenarios and can be used to generate noise effect contour maps for airports.

Contributors

PARTNER
10 YEARS
2003-2013

- Mathias Basner (PI)-Division of Sleep and Chronobiology, Department of Psychiatry, University of Pennsylvania, Perelman School of Medicine
- Patricia Davies (PI)-School of Mechanical Engineering, Purdue University
- Sarah McGuire (Post Doctoral Researcher)-Division of Sleep and Chronobiology, Department of Psychiatry, University of Pennsylvania, Perelman School of Medicine

PARTNER RESEARCH, 2003 – 2013

PUBLIC SYMPOSIUM

Air Quality and Climate Session

Session Chair: Rick Miake-Lye

Opinions, findings, conclusions and recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of PARTNER sponsor organizations.

10th Year Public Symposium
March 1, 2013
Costa Mesa, CA

PARTNER
Partnership for Air Transportation Noise and Emissions Reduction

PARTNER RESEARCH, 2003 – 2013

PUBLIC SYMPOSIUM

Air Quality and Climate Session

Air Quality and Health Impacts of Aircraft Emissions

Presented by: Sarav Arunachalam
University of North Carolina at Chapel Hill

Opinions, findings, conclusions and recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of PARTNER sponsor organizations.

10th Year Public Symposium
March 1, 2013
Costa Mesa, CA

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Motivation

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- There are known emissions of particulate matter and air toxics from aviation activities that could have potential adverse health effects
  - Critical to understand exposure to these to protect public health
- Capability of FAA's Emissions Dispersion Modeling System (EDMS) limited to dispersion of non-reactive air pollutants
- Current representation of aviation emissions in existing air quality models includes several simplified assumptions
  - Need to improve representation of aviation sources in AQMs from 2-d to 3-d
- Both comprehensive 3-d models (e.g. CMAQ) and local-scale dispersion models (e.g. AERMOD) have strengths and weaknesses
  - Need to distinguish between primary and secondary contributions
  - Need to develop methods to leverage monitoring data to inform source attribution
- Need to assess air quality impacts of projected growth in aviation in the presence of decreasing background emissions
  - In reality climate is also changing, and needs to be taken into account

Challenge

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- Develop multiple tools to process / represent aircraft emissions in air quality models (AQMs)
  - Global scale to regional scale meteorological and AQMs
  - Regional scale to local scale dispersion models
  - FAA emissions models to AQMs
- Project growth in activity of aircraft sources
- Project growth in activity of other anthropogenic sources
- Develop / enhance tools to represent aircraft emissions in air quality models at subgrid and grid-scales
- Evaluate models in the context of NAAQS revisions
- Compare AQ impacts from dispersion models vs statistically based regression models derived from monitoring and flight activity data

Research

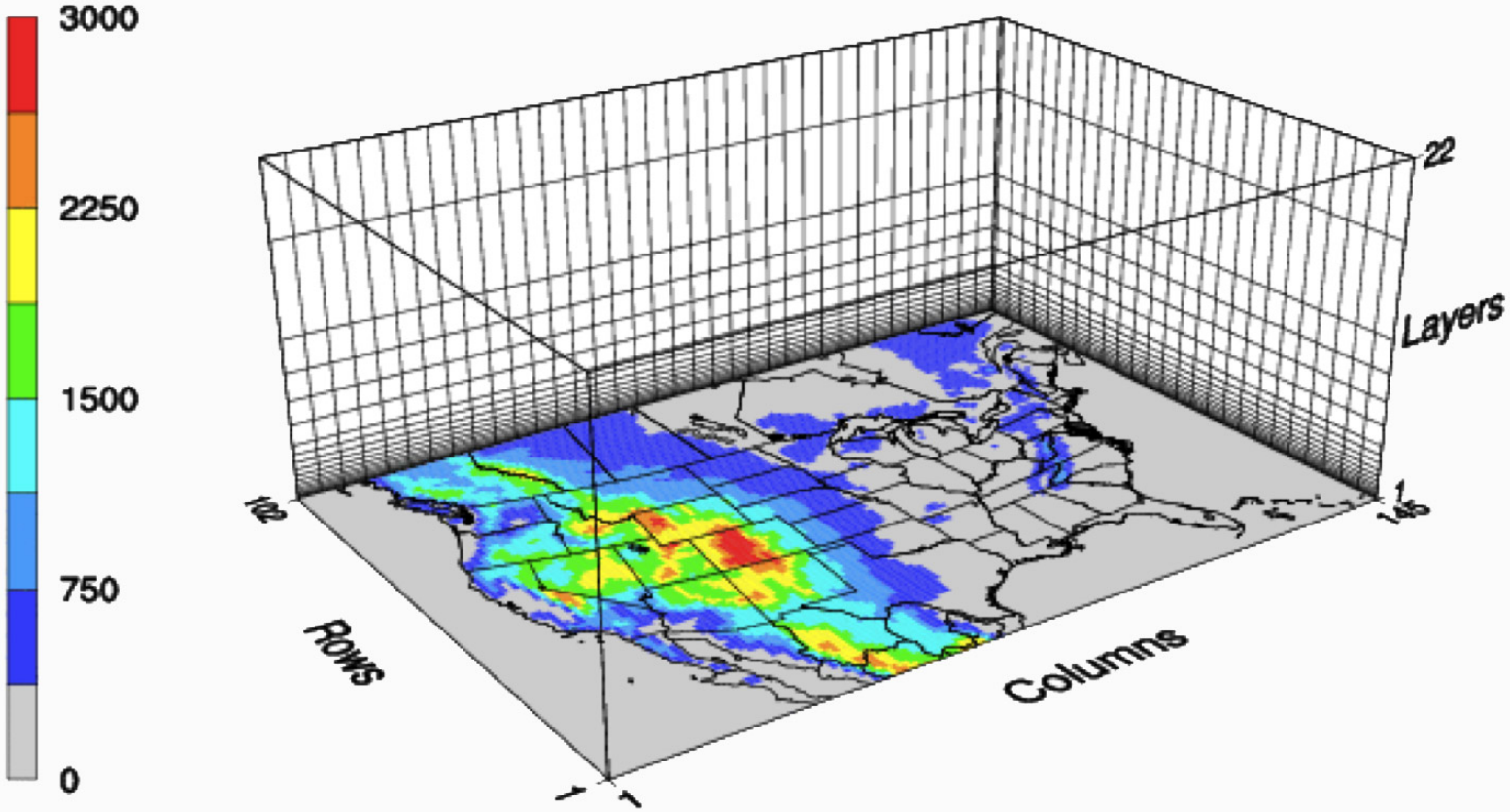
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2003-2013

- Before PARTNER, EDMS was used to estimate emissions from aircraft activities and only dispersion of non-reactive pollutants
  - Complex atmospheric processes that lead to production of secondary pollutants (e.g., O_3, $PM_{2.5}$) ignored
- Transitioned tools to develop air quality applications using EPA's CMAQ modeling system
  - State-of-the-art modeling system that incorporates chemistry, transport and removal of pollutants
  - Used by the EPA for various national-scale regulations and to support regulatory impact analyses (RIA) for NAAQS revisions
  - Developed incrementally refined approach to model aircraft emissions at multiple scales
- Incorporated latest insight on health risks of air pollution, including novel investigation of differential toxicity of particle constituents

Air Quality Modeling Approach

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Traditional Grid-based Modeling



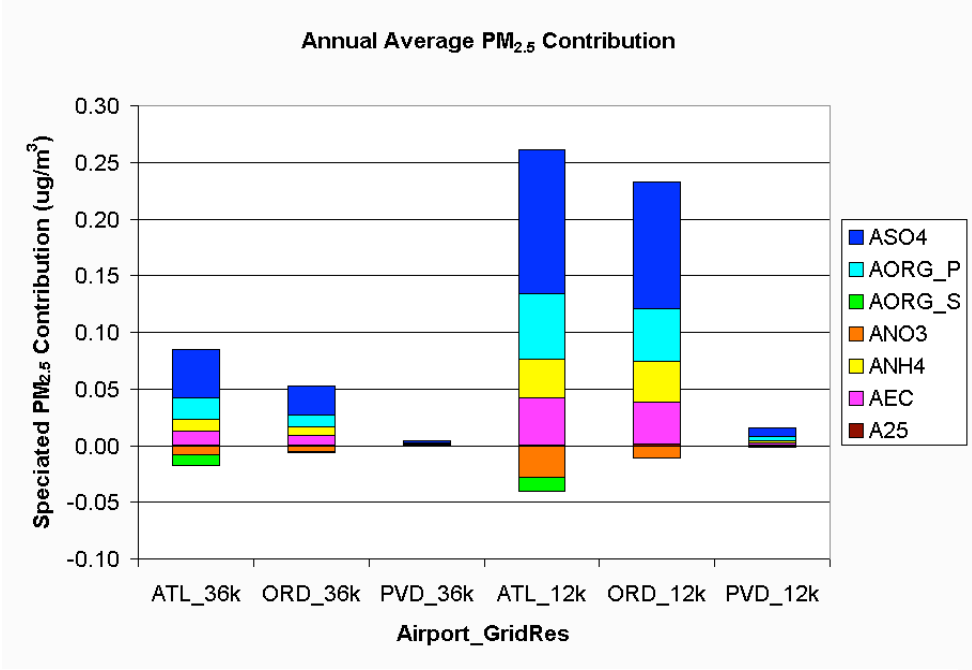
- CMAQ calculates pollutant concentrations in a 3-D grid over the area of interest

Outcomes

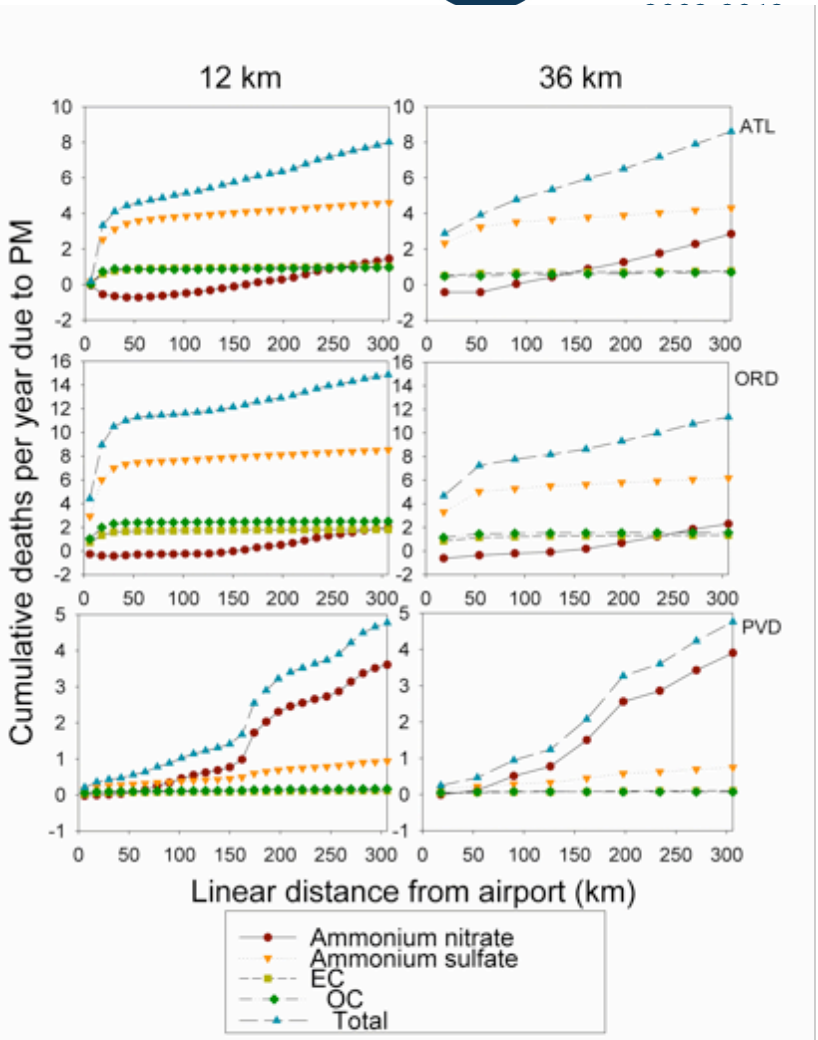
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2003-2013

- Several new interface tools developed, part of FAA Tools
- Key findings from AQ/health risk modeling results
  - Health impacts from $PM_{2.5}$ dominate compared to other pollutants (O_3, air toxics) (Levy et al., 2008)
  - Secondary $PM_{2.5}$ dominates at downwind distances (~200-300 km from airport), while primary components dominate in near field (Arunachalam et al, 2011)
  - Hybrid modeling approach assists with assessing local and regional AQ impacts of aviation
  - Future year AQ impacts of aviation growth dominated by nitrate aerosol, largely due to increase in background free ammonia (Woody et al, 2011)
  - Future year aviation-related health impacts would increase by 6.1x from 2005 to 2025 (2.1x due to emissions, 1.3x due to population, and 2.3x due to background) (Levy et al, 2012)
- Practical Applications
  - Methods and results became basis of refinements in APMT
  - Tools and databases developed used to refine modeling and analyses for the Energy Policy Act (EPAct) study 2010

Air Quality & Health Risk due to Aviation Emissions at Airports



Arunachalam et al, 2011

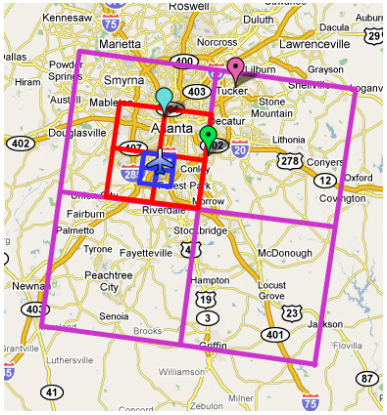


- **Secondary components of $PM_{2.5}$ have health risk impacts close to the airport, but cumulative impacts seen at distances of upto 200-300 km from airport**

Hybrid AQ Modeling at Atlanta Airport

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10 YEARS
2003-2013

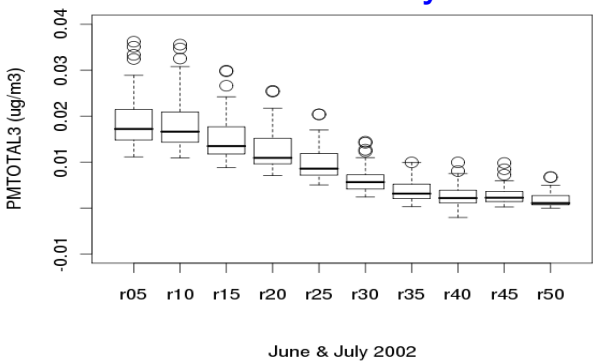
Analyses of $PM_{2.5}$ impacts at radial distances from airport



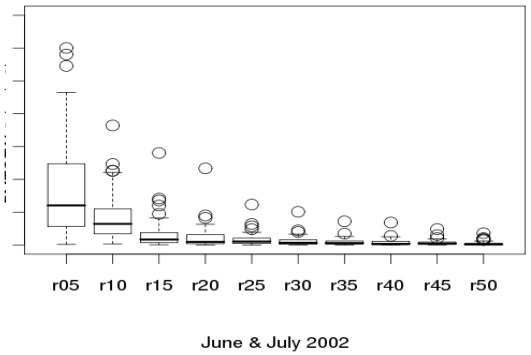
- 36-km grid-cell
- 12-km grid-cell
- 04-km grid-cell

r05: Radius of 5-km
r10: Radius of 10-km
…
r50: Radius of 50-km

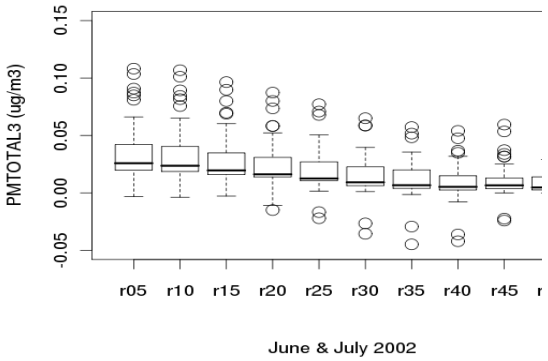
CMAQ-Primary



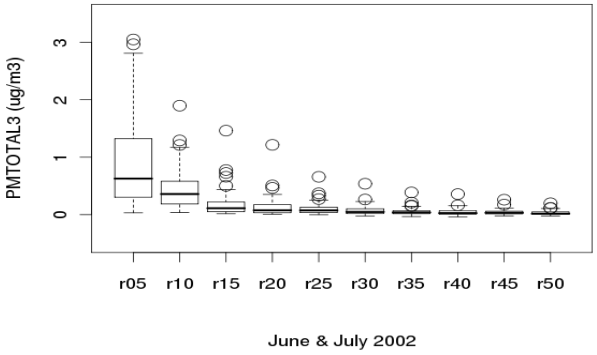
AERMOD



CMAQ-Secondary



Hybrid

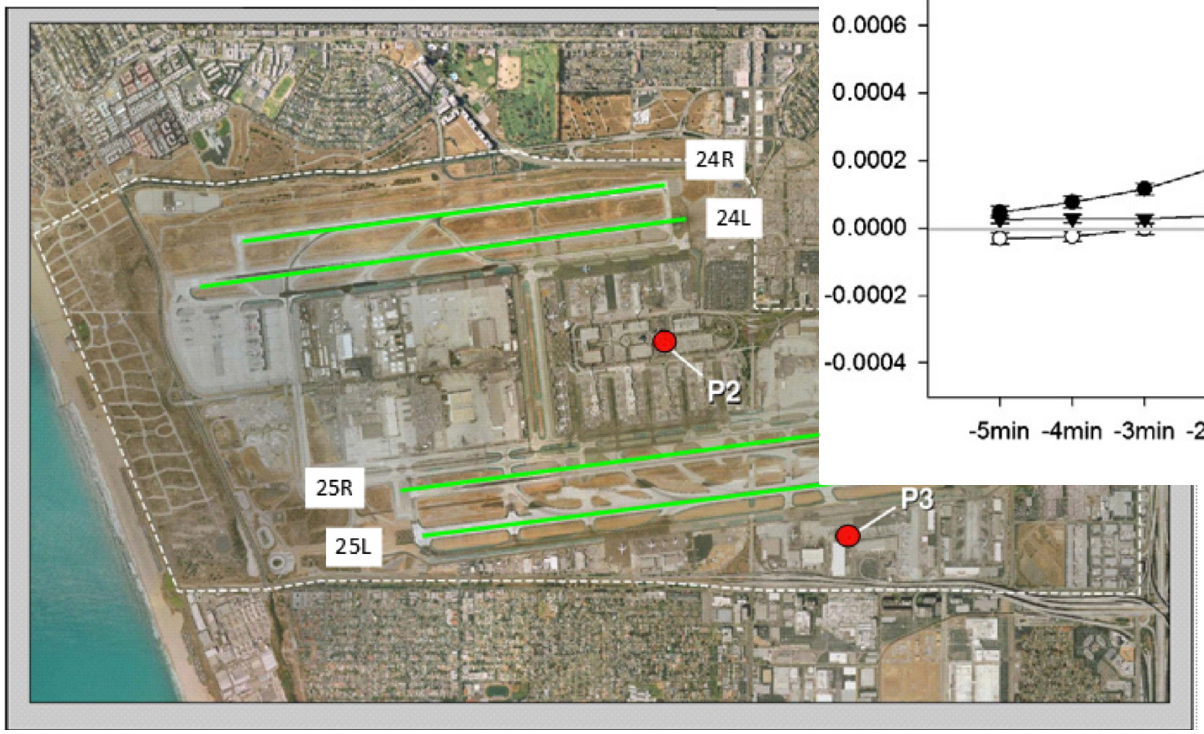


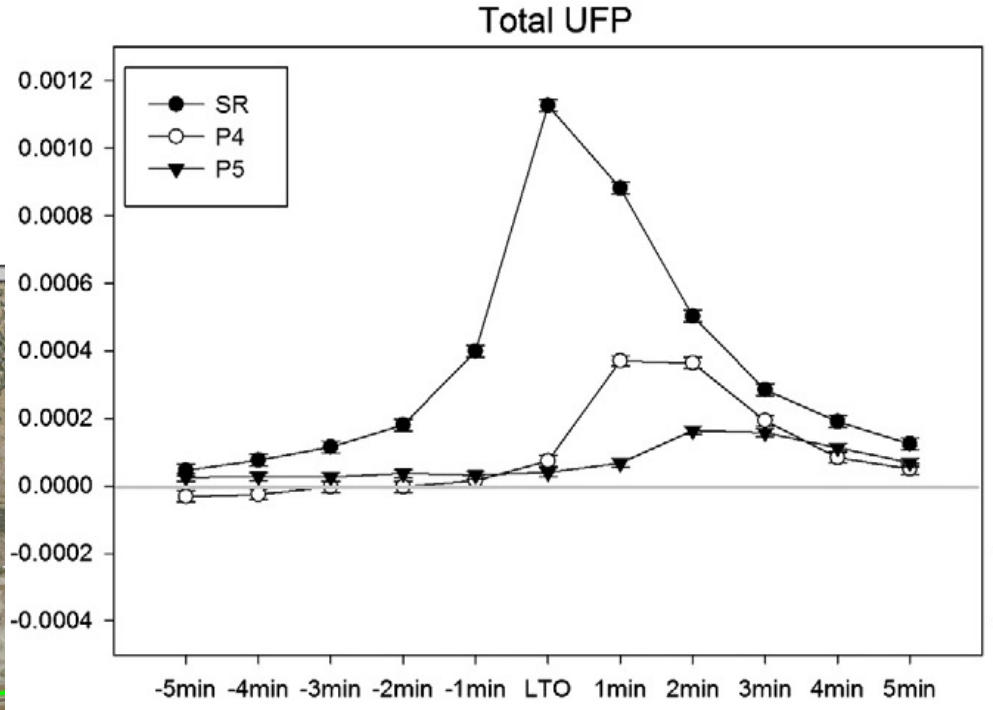
- **AERMOD, CMAQ and Hybrid outputs show decrease in $PM_{2.5}$ concentrations as one goes away from the airport**
- **CMAQ_Secondary > CMAQ_Primary concentrations at all distances from airport**

Monitor-based Regression Model

PARTNER
10 YEARS
2003-2013

Los Angeles International (LAX) Airport





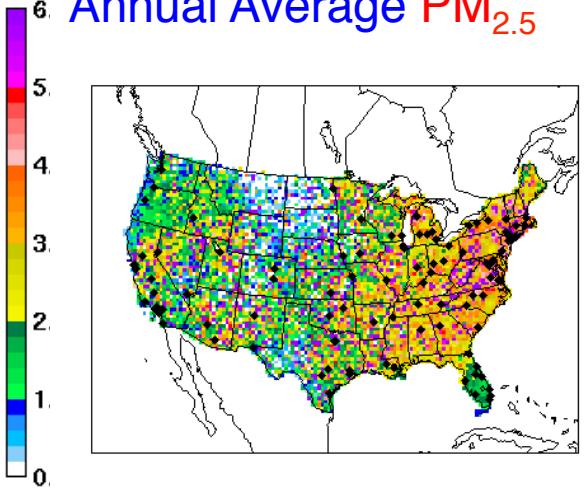
- **Regression model shows elevation in UFP associated with departures on 25R runway, with impact diminishing in magnitude with distance from end of runway. Analytical method allows for determination of incremental contribution of LTO activity from monitoring data (Hsu et al, 2013).**

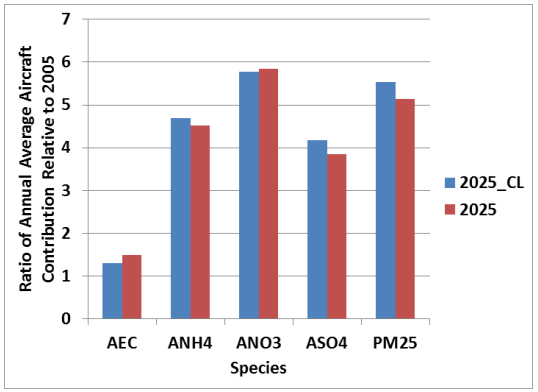
Future Year AQ Impacts of Growth in Aviation from 2005 to 2025

PARTNER
10 YEARS
2003-2013

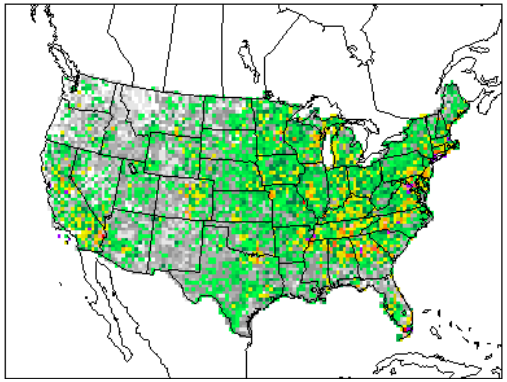
Ratio of 2025 to 2005

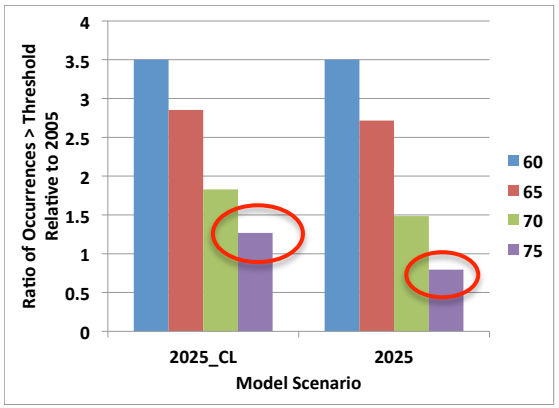
Annual Average $PM_{2.5}$



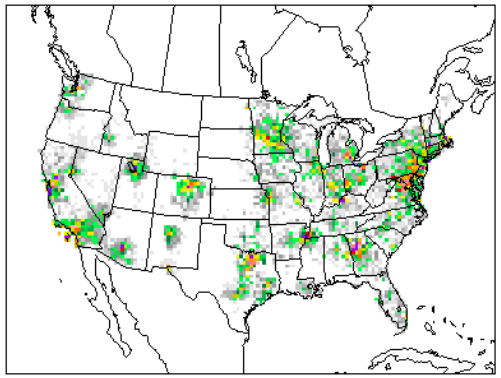


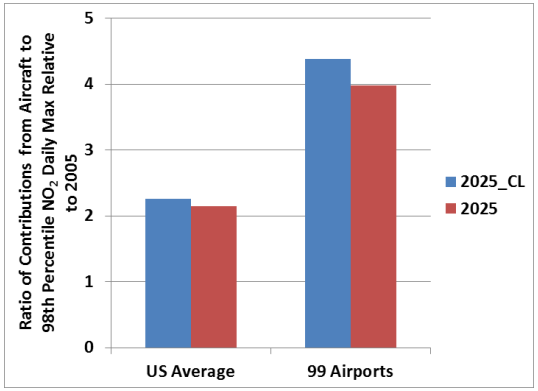
98^{th} Percentile DMax O_3





98^{th} Percentile DMax NO_2





Woody et al, 2011

- Aviation emissions cause a 6x increase in future year $PM_{2.5}$ impacts, mostly from secondary components
- # Grid-cells exceeding O_3 NAAQS (75 ppb) see a 60% ↑ in future year due to change in climate
- Aircraft emissions increase future year NO_2 exceedances by 6x in some major urban areas

Interfaces and Communications

PARTNER
10 YEARS
2003-2013

- External
  - AEC Roadmap Coordinating Council
  - LAWA: LAX Source Apportionment Study Phase II and III
  - Carnegie Mellon University for SOA modeling
  - NCAR for CESM runs for IPCC AR5 outputs
  - ACCRI for Global model outputs
  - Airport Cooperative Research Program
  - Airport Modeling Advisory Committee (AMAC) Panel
  - EPA and state/regional air quality agencies (GA DNR, WRAP)
  - Several conference papers - CMAS, AGU, AMS, NATO/ITM
  - 16 peer-reviewed papers on AQ modeling, monitoring analyses and health impacts
- Within PARTNER
  - Aerodyne, Inc. for Plume model linkage in CMAQ
  - MIT: PARTNER Project 3 – APMT, EPAct Study
  - MIT, Stanford, Cambridge: PARTNER Project 27 – ULS Study
  - Missouri UST: Project 20 – Emissions Measurements
  - Penn State Univ: Project 3
  - BU/Harvard: Project 11

Summary

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2003-2013

- Improved understanding of AQ impacts of aircraft emissions during LTO cycles
- Successfully developed approach to model AQ impact from plume-scales to local-to-regional scales
  - Significant new capability being developed to understand volatile PM impacts
- Successfully developed downscaling tools from global to regional to local-scale models
- Strengthened insights about key exposures associated with health risks from aircraft emissions
- Future year AQ impacts of aviation growth dominated by nitrate aerosol, largely due to increase in background free ammonia
- Future year aviation-related health impacts would increase by 6.1x from 2005 to 2025 (2.1x due to aircraft emissions, 1.3x due to population, and 2.3x due to background emissions)
- New modeling platform with latest tools and databases under development for future policy development

Contributors

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10 YEARS
2003-2013

- UNC
  - Z Adelman, BH Baek, FS Binkowski, S Boone, JH Bowden, N Davis, M Woody, M Omary, J Rissman, U Shankar, K Talgo, A Valencia, P Vennam, A Xiu
- Boston University
  - JI Levy, S Penn (BU), G Adamkiewicz, CD Barr, DM Diez, RE Dodson, F Dominici, Y Dou, EA Houseman, HH Hsu, SJ Melly, JD Spengler, J Vallarino, Y Zhou
- Aerodyne
  - H-W Wong and RC Miake-Lye (Aerodyne)
- A Robinson (CSU), S Jathar (UC Davis)
- U.S. EPA OAQPS and ORD, Rhode Island DEM, LAWA, Georgia DNR, WRAP, UT Knoxville

Publications

1. Adamkiewicz G, et al., Nitrogen dioxide concentrations in neighborhoods adjacent to a commercial airport: a land use regression modeling study. *Environ Health*, 2010.
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3. Barrett S, et al. Public Health, Climate and Economic Impacts of Desulfurizing Jet Fuel, *Environ. Sci. and Tech., 2012.*
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5. Diez DM, et al., Statistical approaches for identifying air pollutant mixtures associated with aircraft departures at Los Angeles International Airport. *Environ Sci Technol*, 2012.
6. Dodson RE, et al, An analysis of continuous black carbon concentrations in proximity to an airport and major roadways*, Atmos. Environ.*, 2009.
7. Hsu HH, et al., Using mobile monitoring to characterize roadway and aircraft contributions to ultrafine particle concentrations near a mid-sized airport. Submitted.
8. Hsu HH, et al., Contributions of aircraft arrivals and departures to ultrafine particle counts near Los Angeles International Airport. *Sci Tot Environ*, 2013.
9. Levy JI, et al., A meta-analysis and multi-site time-series analysis of the differential toxicity of major fine particulate matter constituents. *Am J Epidemiol*, 2012.
10. Levy JI, et al., Current and Future Particulate-Matter-Related Mortality Risks in the United States from Aviation Emissions During Landing and Takeoff, *Risk Analysis*, 2012.
11. Rissman J, et al., A plume-in-grid approach to characterize air quality impacts of aircraft emissions at the Hartsfield-Jackson Atlanta International Airport, *Atmos. Chem. Phys. Discuss.*, 2013.
12. Rissman J, et al., Equity and Health Impacts of Aircraft Emissions at the Hartsfield-Jackson Atlanta International Airport, *Landscape and Urban Planning,* Submitted.
13. Woody M, et al,, An Assessment of Aviation's Contribution to Current and Future Fine Particulate Matter in the United States, *Atmos. Environ.*, 2011.
14. Woody M and S. Arunachalam, Secondary Organic Aerosol Produced from Aircraft Emiissions at the Atlanta Airport: An Advanced Diagnostic Investigation Using Process Analysis, Submitted, 2012.
15. Zhou Y and JI Levy, Between-airport heterogeneity in air toxics emissions associated with individual cancer risk thresholds and population risks. *Environmental Health*, 2009.
16. Zhou Y and JI Levy, Predictors of heterogeneity in airport emissions of air toxics associated with individual cancer risk thresholds, *Epidemiology*, 2008.

PARTNER RESEARCH, 2003 – 2013

PUBLIC SYMPOSIUM

Metrics for Aviation Effects on Climate: What Have We Learned?

Overview

Presented by: Don Wuebbles, University of Illinois

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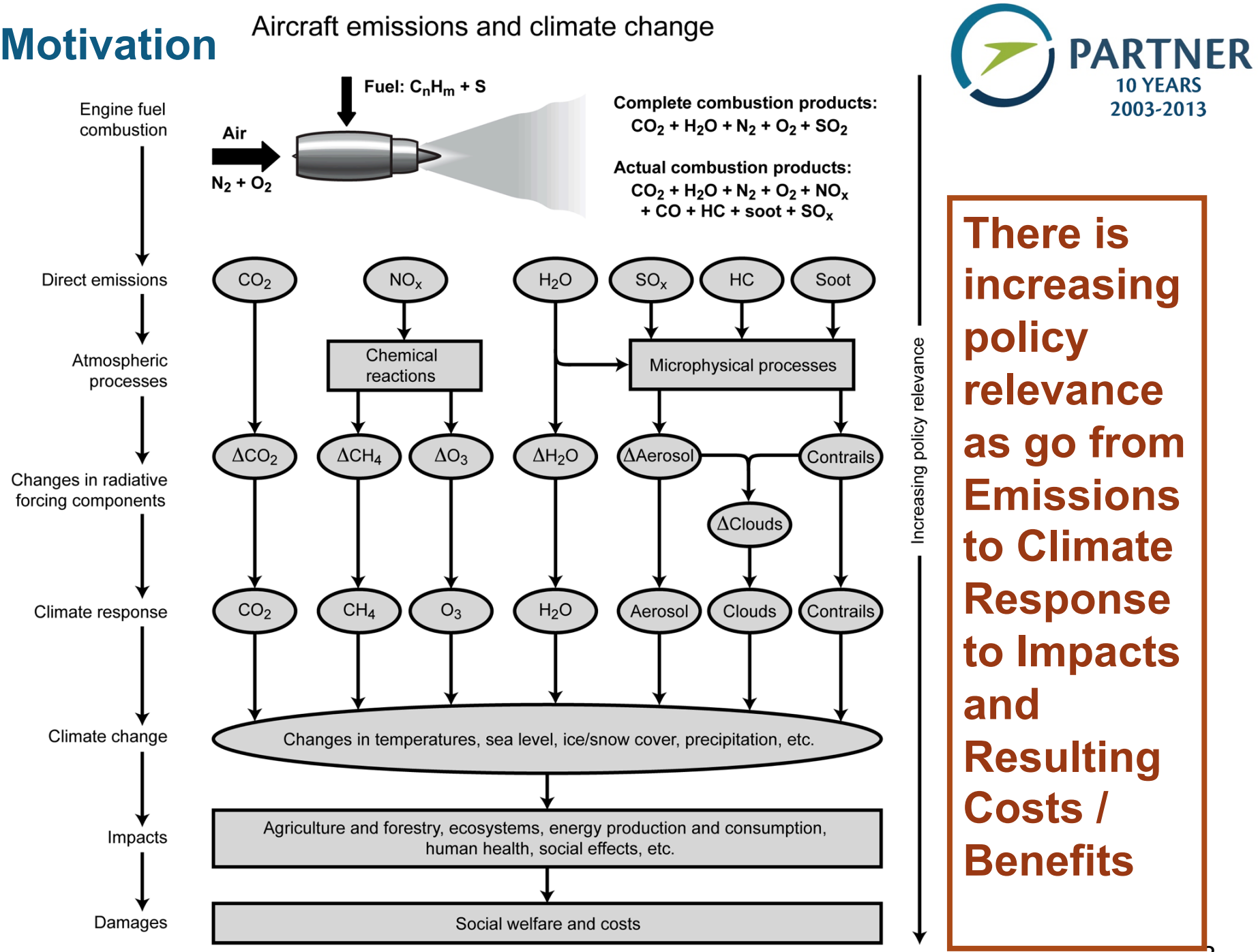
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Coauthors

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10 YEARS
2003-2013

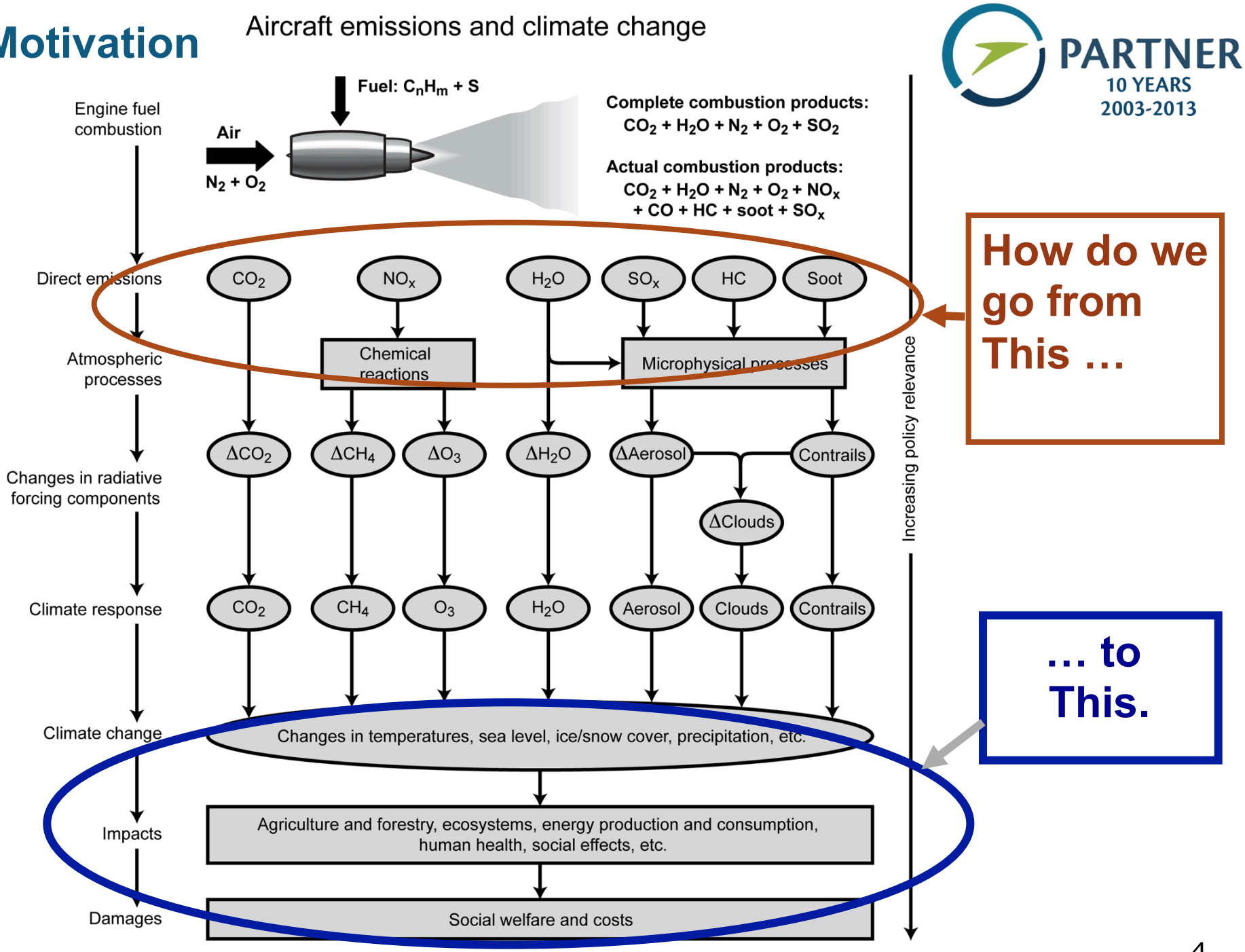
- Steven Barrett, MIT
- Piers Forster, University of Leeds, UK
- Jan Fuglestvedt, CICERO, Norway
- Arezoo Khodayari, University of Illinois
- Seth Olsen, University of Illinois
- Ron Prinn, MIT
- Alex Rap, Post-doc, University of Leeds, UK

Motivation



There is increasing policy relevance as go from Emissions to Climate Response to Impacts and Resulting Costs / Benefits

Motivation


Aircraft emissions and climate change
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2003-2013
Fuel: C_nH_m + S
Air
N_2 + O_2
Engine fuel combustion
Complete combustion products:
CO_2 + H_2O + N_2 + O_2 + SO_2
Actual combustion products:
CO_2 + H_2O + N_2 + O_2 + NO_x + CO + HC + soot + SO_x
Direct emissions
CO_2
NO_x
H_2O
SO_x
HC
Soot
Atmospheric processes
Chemical reactions
Microphysical processes
Changes in radiative forcing components
ΔCO_2
ΔCH_4
ΔO_3
ΔH_2O
ΔAerosol
Contrails
ΔClouds
Climate response
CO_2
CH_4
O_3
H_2O
Aerosol
Clouds
Contrails
Climate change
Changes in temperatures, sea level, ice/snow cover, precipitation, etc.
Impacts
Agriculture and forestry, ecosystems, energy production and consumption, human health, social effects, etc.
Damages
Social welfare and costs
Increasing policy relevance
How do we go from This …
… to This.

Challenge

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Climate impacts and climate metrics

- **Radiative forcing has traditionally been the primary metric for climate analyses**
- **Radiative forcing (RF) not adequate**
  - at minimum needs to include efficacy for various climate effects.
  - Does not consider the time dependence of the emissions.
- **A refined RF may be still be useful, but also need emissions based metrics**
  - **Emissions based metric are used in assessing other energy / transportation/ industry sources of concern to climate.**
- **There likely is no single perfect metric -- the specific metric needed likely depends on the questions being asked.**

Emissions Based Metrics

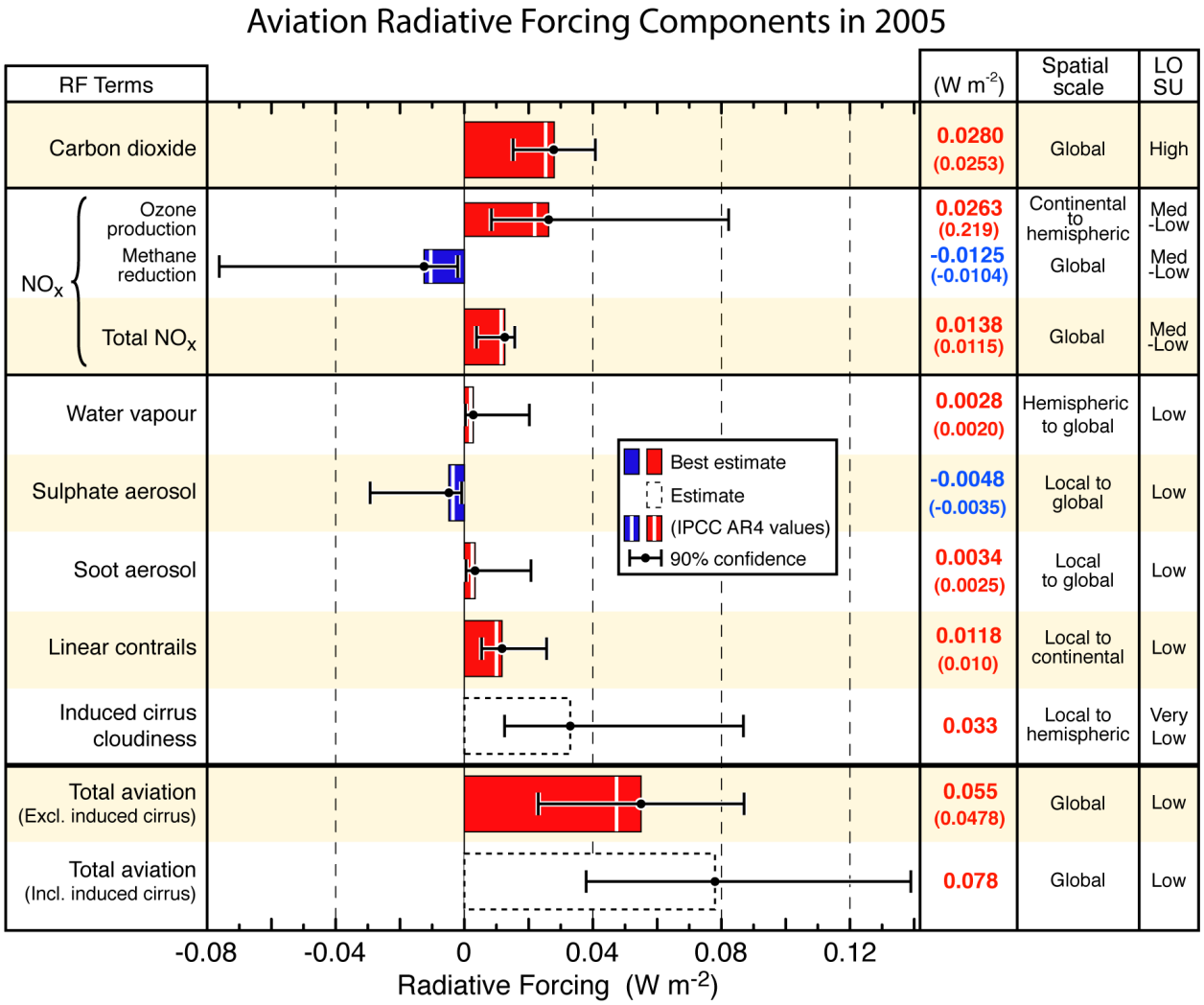
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- Global Warming Potentials (GWPs)
  - Developed by Wuebbles, Rodhe, and Derwent for IPCC
  - Metric often used in existing climate policy
- Global Temperature Potentials (GTPs)
  - Shine et al. (2005)
  - Assumes pulse or sustained emissions
  - Sensitive to assumptions in the inputs (e.g., modeling studies)
- Integrated GTPS (IGTPs)
  - Peters et al. (2011)
  - Values generally similar to GWPs
- Simple Climate Models
  - Linearized Temperature Response (LTR)
    - Marais et al. (2007); Grewe and Stenke (2007)
  - Other simplified climate models

RF from Aviation (Lee et al., 2009)

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Note: Not directly relevant for policymaking

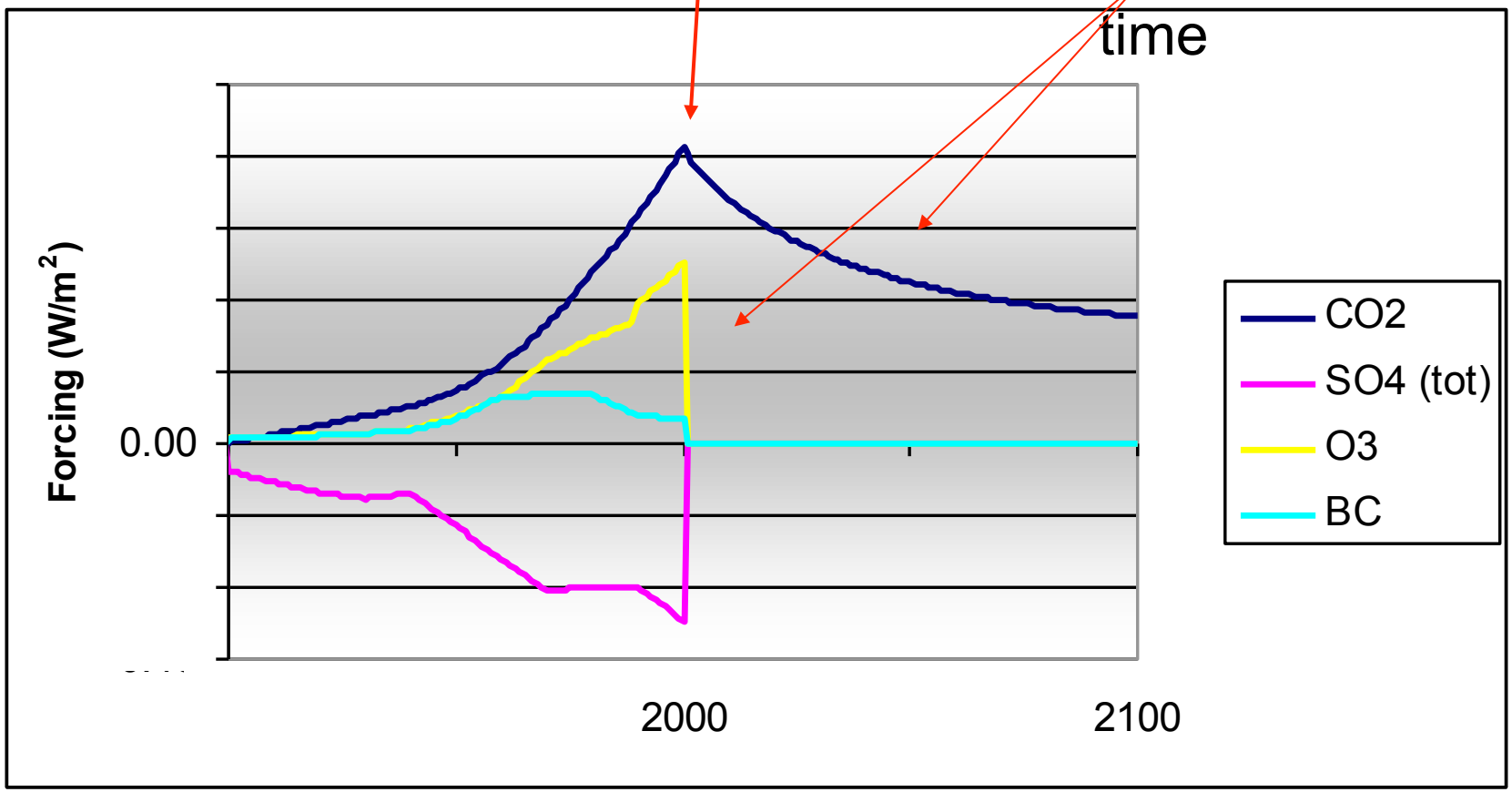


Radiative forcing: (usually) given relative to pre-industrial times but aviation is different

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RF_{2000} is a function of emission history

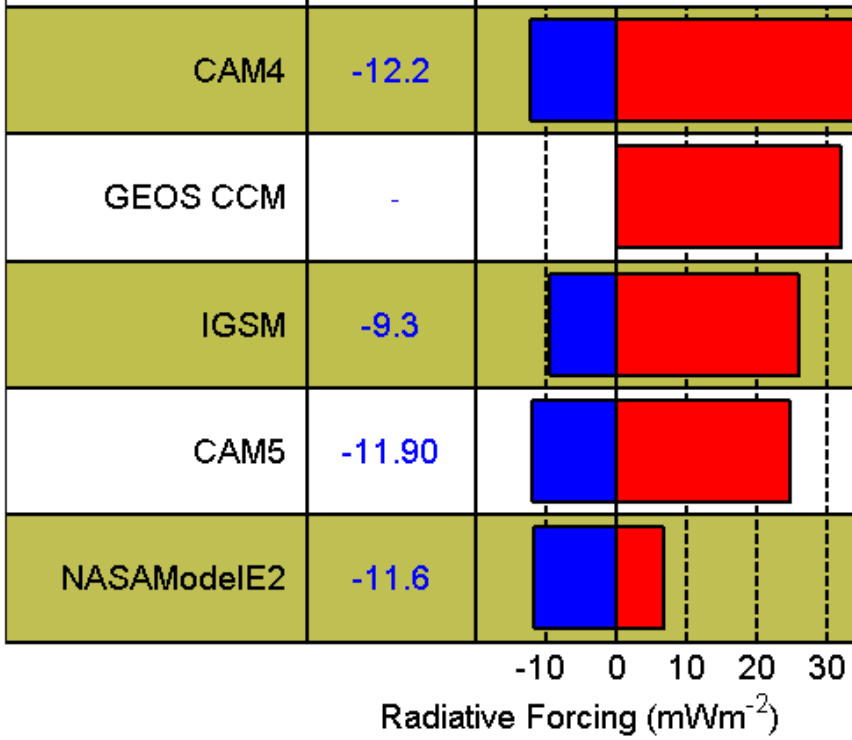
Very different behaviour after this time



New ACCRI Analyses: Relatively large model differences in O_3 and CH_4 RFs

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Model	CH4 RF mWm^{-2}	Short-term O_3 RF mWm^{-2}
CAM4	-12.2	36.53
GEOS CCM	-	32.0
IGSM	-9.3	26.0
CAM5	-11.90	24.90
NASAModelE2	-11.6	6.8



- O_3: 7 - 37 mW/m^2
- CH_4: -9 to -12 mW/m^2
- Net NOx RF < 0 for NASA ModelE2 for all scenarios

Transient vs Steady-State Aviation NOx induced RFs

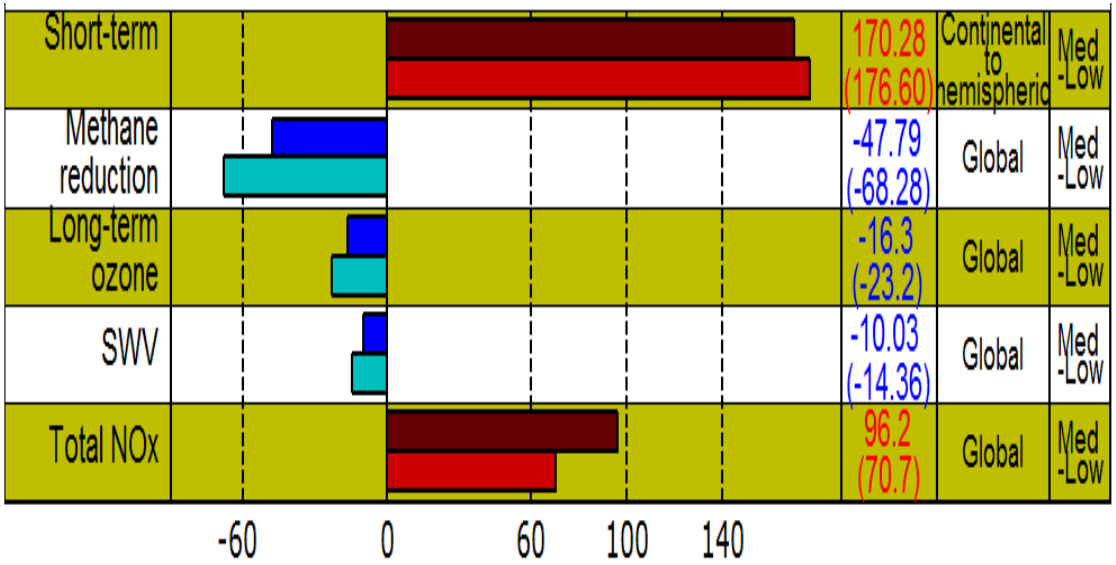
Steady-state (SS) RFs

- use annually repeating emissions for given year
- typical of 3-D CCMs

Transient RFs

- account for time-history of emissions up to year of interest
- account for different lifetimes/ timescales of species, e.g., CH_4
- too expensive for CCMs
- use relationships from CCMs

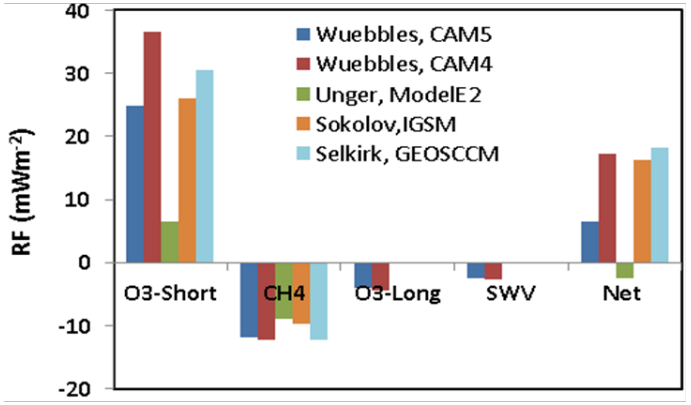
2050 Baseline RFs
Transient (top bars), SS (bottom bars)

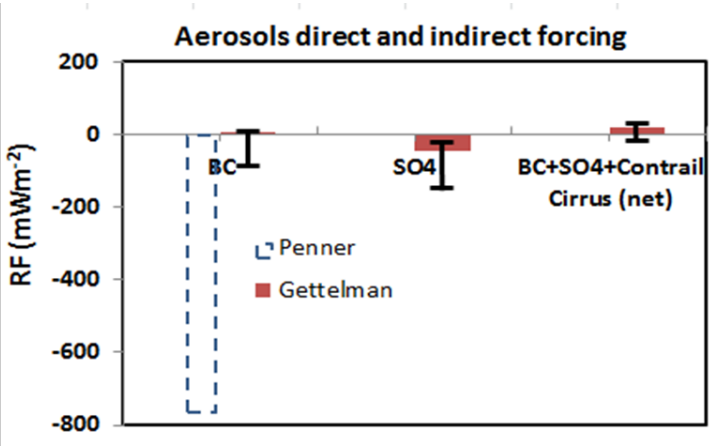


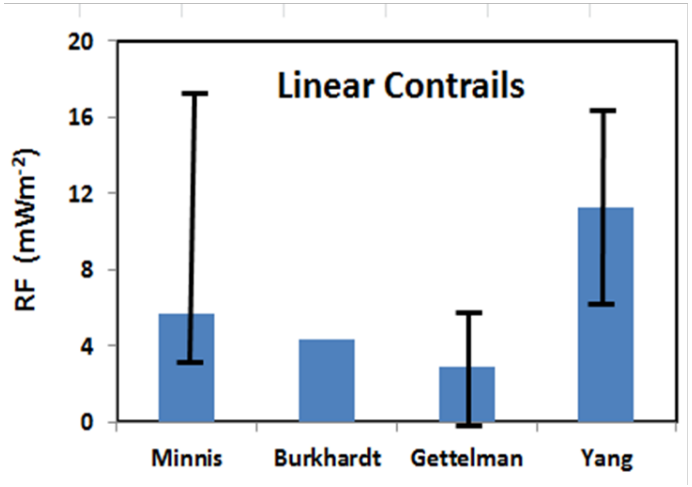
Transient RFs higher are than SS RFs by
~22% for AEDT 2005
~10% for AEDT 2050 Scenario1
~36% for AEDT 2050 Baseline

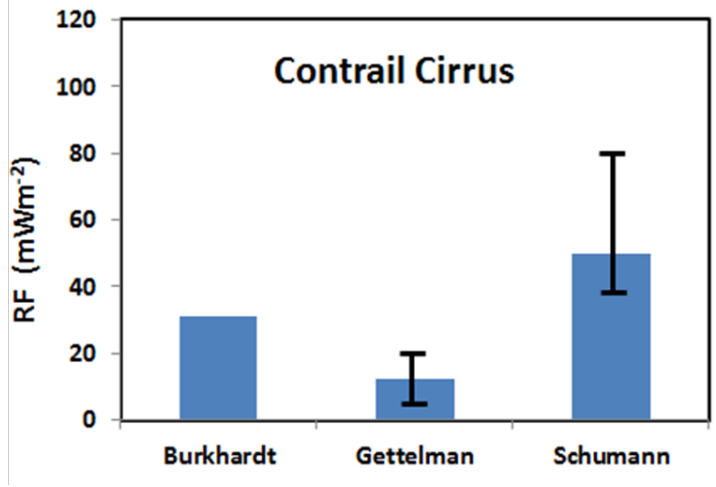
Individual Components of Aviation RF for 2006 Emissions

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2003-2013





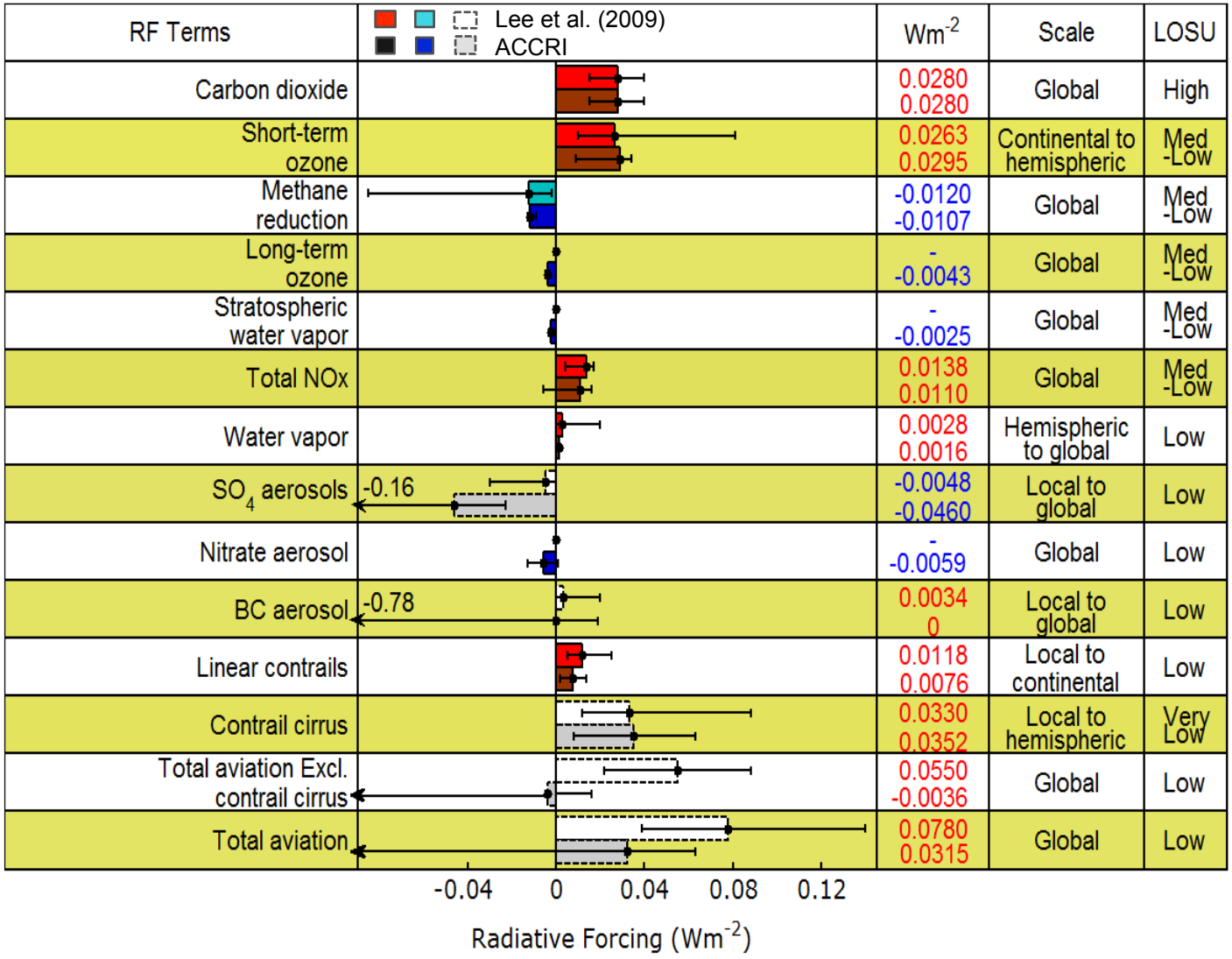




Penner estimate of BC RF (shown as a dashed bar) represents the reported range with current modleing assumptions, but no best estimate was reported

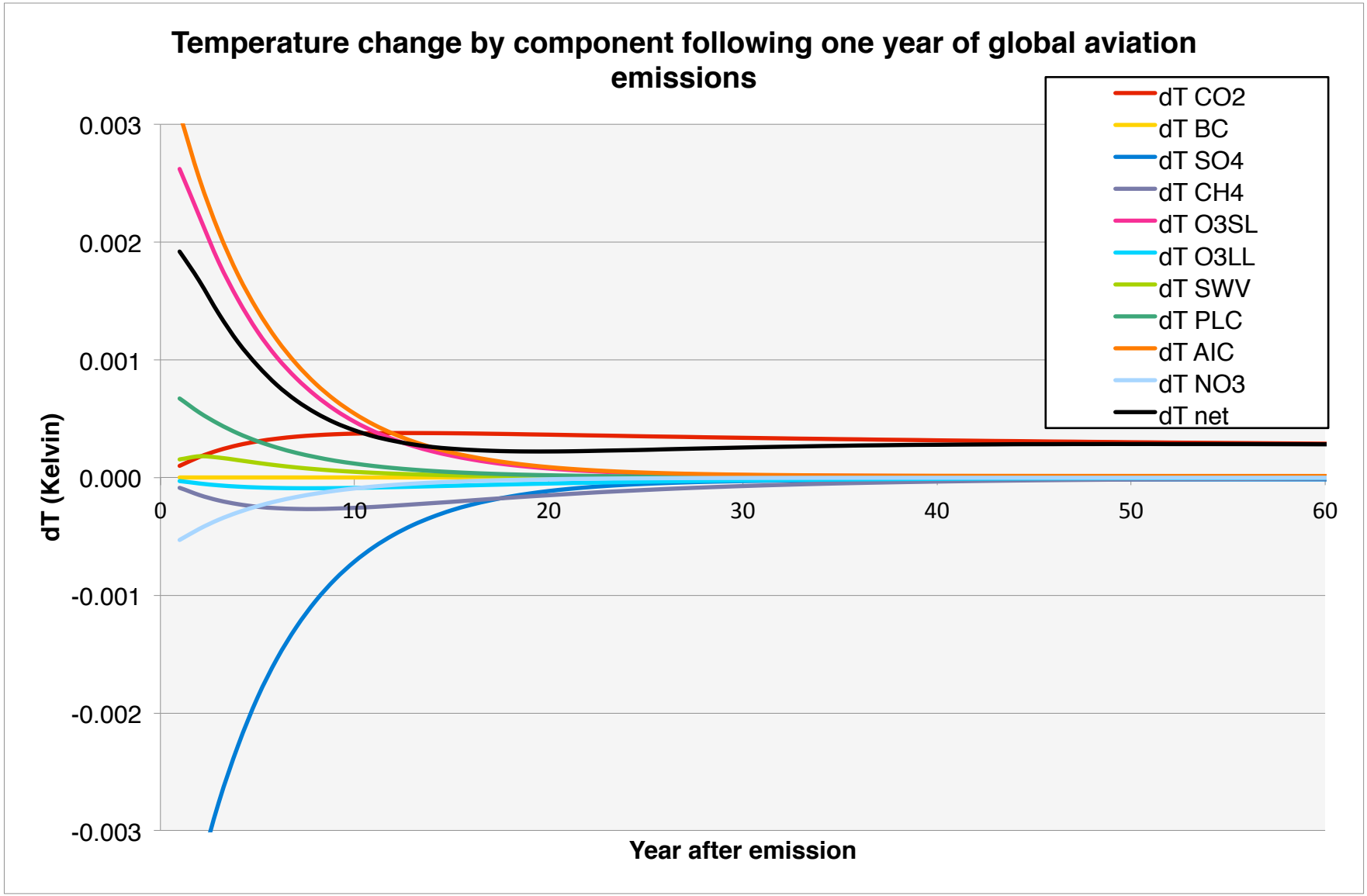
RF for 2006 Global Aviation Emissions: Lee versus ACCRI

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2003-2013

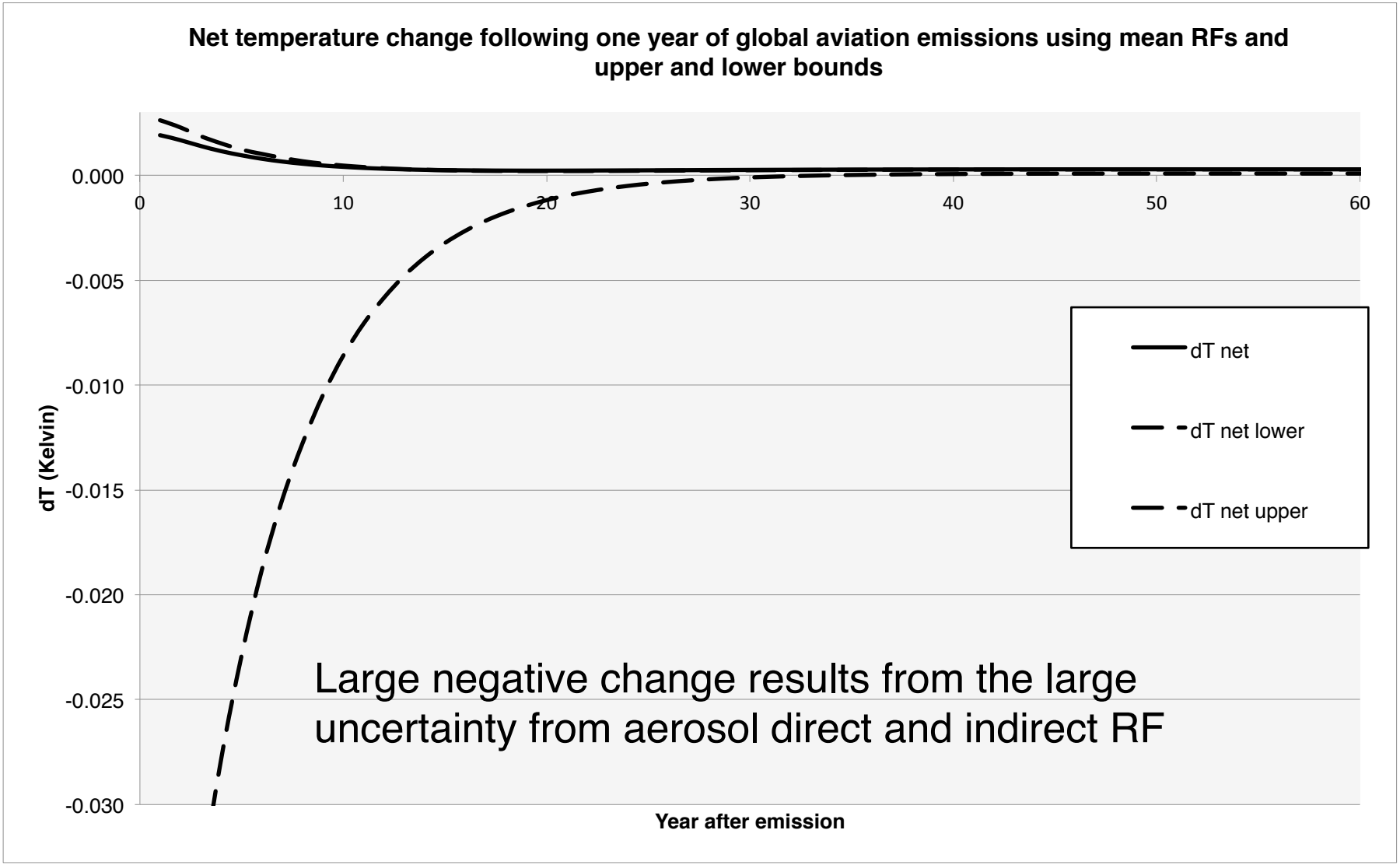


Change in Temperature from Aviation for 1 year pulse

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Range in the net change in temperature with time due to the one year aviation perturbation

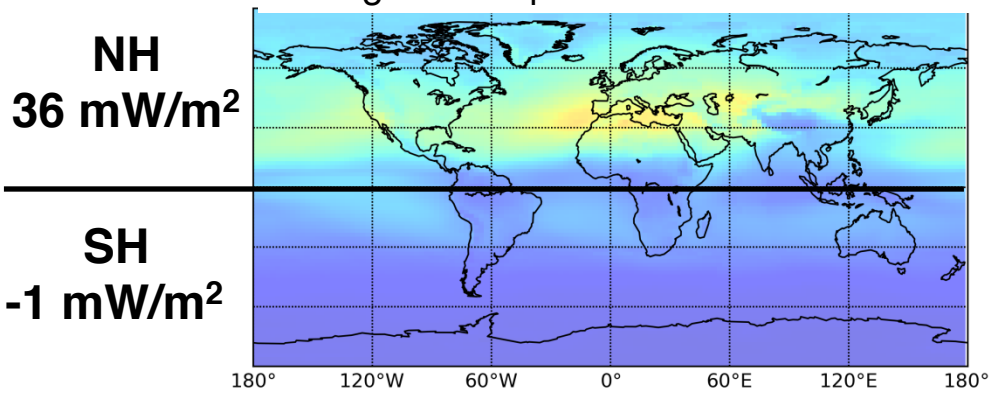


Regional RFs: Regional Effects Need to consider in Global Metrics

- Most simple climate models/metrics use global average forcings but for aviation
- NH forcing ~2 x SH forcing
- Forcings with largest asymmetries are also those with largest uncertainties
- Need regional metrics

New studies by Olsen et al. and Lund et al.

O_3 + CH_4 RF from CAM4



RFs	NH	SH	Global
CO_2	29	29	29
CH_4	-10 (1.8)	-10(1.8)	-10(1.8)
O_3-long*	-7	-7	-7
O_3-short	**35(18)**	**14(8)**	**25 (13)**
Aerosols	**-52(29)**	**-4(1)**	**-24(14)**
Contrails/ Cirrus	**60(36)**	**3(2)**	**31(20)**
Total	**55(49)**	**25(9)**	**44(28)**

Average (stddev) from ACCRI models that reported hemispheric forcings *O3 long from CAM4

Simple Climate Models (SCMs) Analyses and Intercomparison

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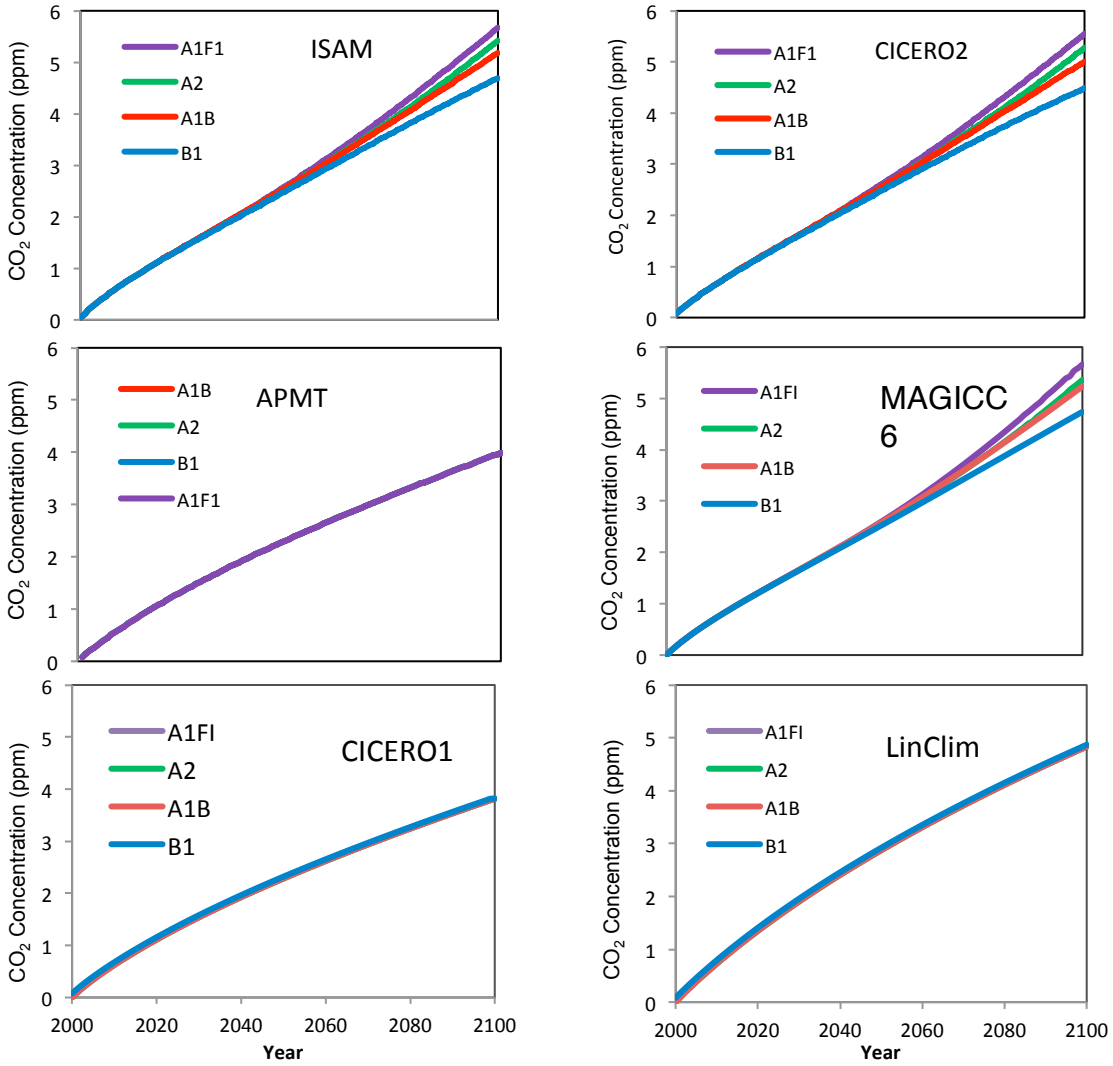
Models	Carbon Cycle Sub-model	Energy balance sub-model
APMT	IRF	1-Box (just mixed layer)
CICERO-1	IRF	2-Box (mixed layer + deep ocean)
CICERO-2	Non-linear Process specific	hemispheric upwelling-diffusion-ocean model
ISAM	Non-linear Process specific	upwelling-diffusion-ocean model
LinClim	IRF	IRF tuned to ECHAM5/MPI-OM $2xCO_2$ experiment
MAGICC6	Non-linear Process specific	hemispheric upwelling-diffusion-ocean model

Impulse response function (IRF) assumes a linear response.
It is a sum of exponentially decaying functions with fixed coefficients obtained by calibration to a parent 3-D climate model.

Carbon Cycle: Limitation of Simple Atmospheric IRF

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Response to constant CO_2 emissions of 654 Tg/yr under different IPCC SRES background CO_2 emission scenarios



CO_2 airborne % should depend on background atmosphere. Did it?

No: APMT, CICERO-1and LinClim

Yes: CICERO-2, ISAM and MAGICC6

Carbon Cycle Sub-Model: Key Finding

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APMT, LinClim and CICERO-1 by using a single IRF give lower CO_2 concentrations than ISAM , CICERO-2, MAGICC and IPCC. Including non-linearities in ocean chemistry is necessary for projecting the future CO_2 concentration.

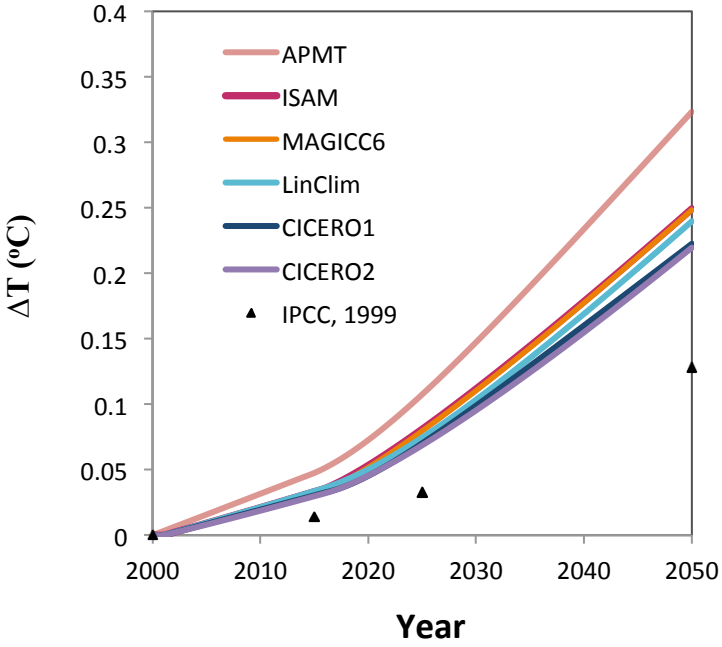
Use the single IRF which describe atmospheric changes in CO_2 in combination with separate equations describing air-sea and air-biosphere exchange of CO_2.

APMT adopted Bern intermediate complexity carbon cycle model (also used in CICERO-2)

Energy Balance Sub-Model: Key Finding

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Aviation-induced temperature change produced by forcing SCMs energy balance sub-models with radiative forcings for Edh aviation scenario from IPCC (1999).



- AMPT with the Shine energy balance sub-model (one-box slab ocean) results in a higher temperature projection for CO_2 and non-CO_2 aviation emissions.

- Recommendation: include heat exchange with deep ocean using 2-box or multi-box ocean sub-model.

Result: APMT now using the CICERO-1 energy balance model

ACCRI and PARTNER have had an impact

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- **New RF analyses based on ACCRI models show much larger uncertainties than recognized previously.**
  - This is largely related to the transition to new highly complex coupled climate-chemistry models.
  - Differences especially large for NOx and aerosol emissions
- **Large regional (e.g., hemispheric) differences in RF**
- **Simple Climate Models like APMT can be extremely useful in policy analyses**
  - Analyses have further improved the carbon cycle, energy balance analyses, and representation of aviation effects in such models
- **Further analyses needed for metrics (GWPs, etc.) to determine their effective use for aviation.**
  - Need to make clear what they are telling us – and not telling us
  - GTPs and GWPs are fundamentally different
  - GTPs more relevant but more uncertain (ocean response model, etc.)

PARTNER RESEARCH, 2003 – 2013
PUBLIC SYMPOSIUM

Tools and Policy Analysis

Session chair: Christopher Roof

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10th Year Public Symposium
March 1, 2013
Costa Mesa, CA

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Partnership for Air Transportation Noise and Emissions Reduction

Tools and Policy Analysis Outline

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2003-2013

- Introduction to Tools

  Christopher Roof - Volpe Center

- APMT and Application for ICAO Policies

  Anuja Mahashabde - Mitre

ICAO: International Civil Aviation Organization

PARTNER RESEARCH, 2003 – 2013
PUBLIC SYMPOSIUM

Introduction to Tools

Presented by: Christopher Roof, Volpe Center

Volpe The National Transportation Systems Center
Advancing transportation innovation for the public good

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Motivation

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- ~2004: Progress in reducing aviation environmental impacts, but robust, integrated capability required
- Interdependencies, interdependencies, …
  - Noise, fuel burn and emissions
  - Solutions: technology vs. policy
  - Benefit/cost
  - Resource investment planning
  - Consistency across FAA analyses
- Carbon neutral growth

Challenge

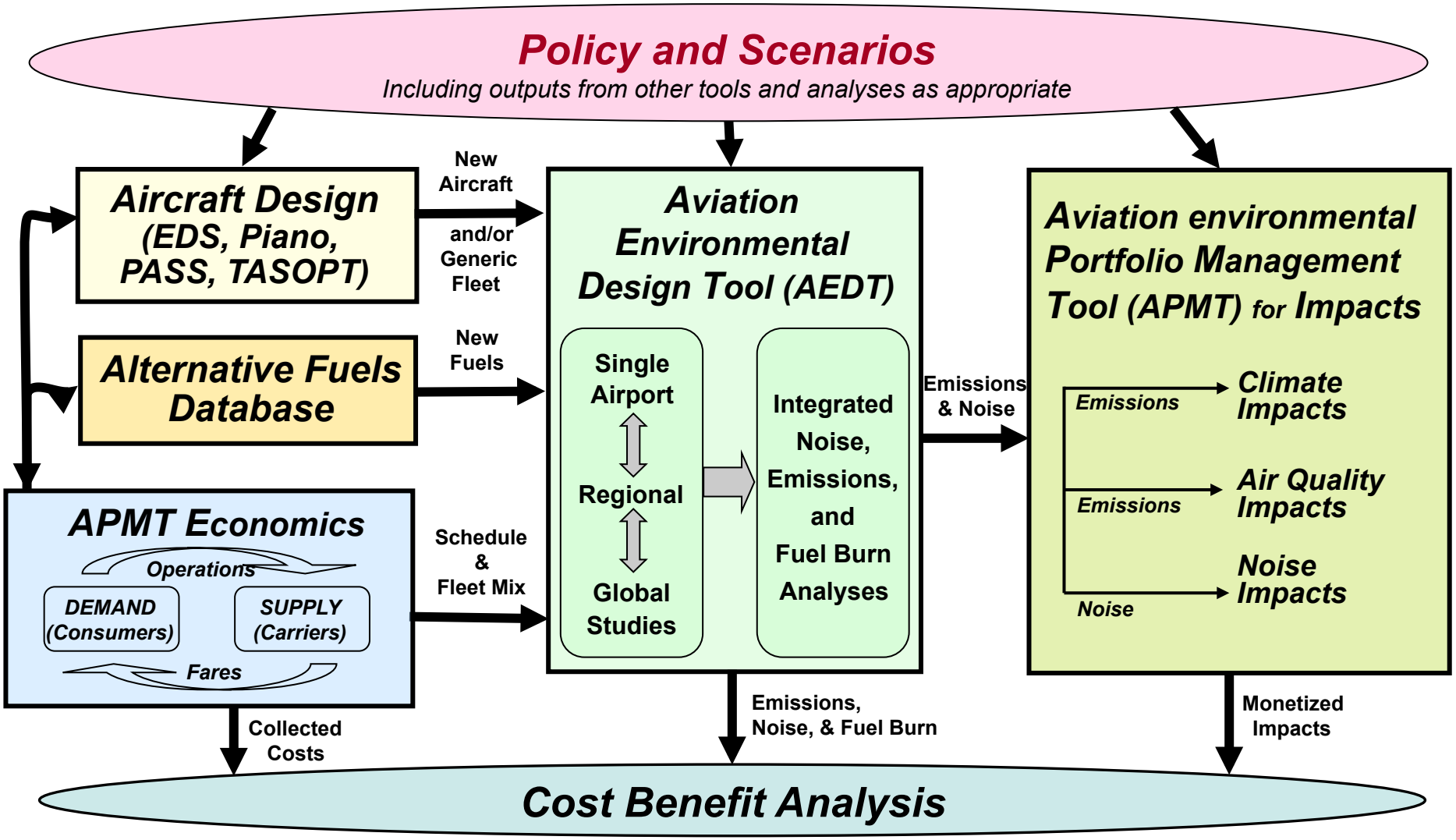
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"Need a comprehensive toolset for analyzing interdependencies between aviation-related noise and emissions, as well as ability to perform cost-benefit analyses to inform decision makers"

Dr. Lourdes Maurice, National Academy of Science Workshop (2004)

Challenge

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EDS: Environmental Design Space Piano: (Aircraft Emissions and Performance tool)
PASS: (Program for Aircraft Synthesis Studies) TASOPT: Transport Aircraft System OPTimization

Research

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- Early 2000's:
  - 5 distinct tools for aviation environmental consequences:
    - EDMS, INM, MAGENTA, NIRS & SAGE
  - Inconsistencies in analyses
    - Scale: Local vs. Regional vs. NAS vs. Global
    - Interdependencies: Noise vs. Fuel burn vs. Emissions
    - Inability to fully understand policy implications with single analysis

- AEDT
- APMT
- EDS

} *Data-driven, scalable, integrated tools suite*

AEDT: Aviation Environmental Design Tool APMT: Aviation environmental Portfolio Management Tool EDMS: Emissions and Dispersion Modeling System EDS: Environmental Design Space INM: Integrated Noise Model MAGENTA: Model for Assessing Global Exposure to the Noise of Transport Aircraft NIRS: Noise Integrated Routing System SAGE: System for assessing Aviation's Global Emissions

Outcomes

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2003-2013

- Initial sample problems: NOx Stringency
- Actual Policy Analysis
  - NOx Stringency
  - Goals Analysis
  - Journal articles & PARTNER technical reports

} ***Complete***

- Unprecedented Uncertainty Analysis

http://www.faa.gov/about/office_org/headquarters_offices/apl/research/models/aedt/media/AEDT_2a_Uncertainty_Quantification_Executive_Summary.pdf

- Future Policy Analysis
  - Global CO2 Standard
- Does this make a difference?
  - Policymakers now better informed
  - Interdependent analyses possible
  - Common data/methodologies

Outcomes

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10 YEARS
2003-2013

- Policy Analysis
  - Global Noise Stringency

-> AEDT key to understanding interdependencies

"This new noise standard is an important step for aviation and will provide a much quieter environment for the many communities living in proximity to the world's airports"

ICAO Secretary General, Raymond Benjamin

AEDT: Aviation Environmental Design Tool ICAO: International Civil Aviation Organization

Interfaces and Communications

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- External
  - Design Review Group
  - SAE International - Aircraft Noise Measurement and Noise/Emissions Modeling Committee (A-21)
  - Airports Council International
  - ICAO CAEP Modeling and Database Group
  - Aviation Climate Change Research Initiative (ACCRI)
  - FAA Tools web sites
    https://aedt.faa.gov/Default-Live.aspx
    http://www.faa.gov/about/office_org/headquarters_offices/apl/research/models/
- Within PARTNER
  - EDS – Georgia Tech
  - APMT – MIT, MVA
  - Acoustics Research groups
  - Emissions Research groups

APMT: Aviation environmental Portfolio Management Tool CAEP: Committee on Aviation Environmental Protection
EDS: Environmental Design Space ICAO: International Civil Aviation Organization

Summary

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- **Policymakers at all levels now have interdependency analytical tool capabilities**
- Next steps: Bring more fruits of PARTNER research into FAA Tools
  - AEDT Version 2B release: 2014
  - Further improvements
    - Acoustic propagation
    - Particulate matter emissions
    - Integrated analyses with alternation fuels
    - Health effects

Contributors

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10 YEARS
2003-2013

- FAA AEE Management and Technical staff
- Volpe Center
- ATAC
- CSSI
- Metron
- Wyle
- Georgia Tech
- MIT

Thank you…

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10 YEARS
2003-2013

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PARTNER RESEARCH, 2003 – 2013

PUBLIC SYMPOSIUM

Assessing Costs and Benefits of Aviation Environmental Policies

ICAO CAEP/8 NOx Stringency Analysis

Presented by: Anuja Mahashabde, MITRE Corporation

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Motivation

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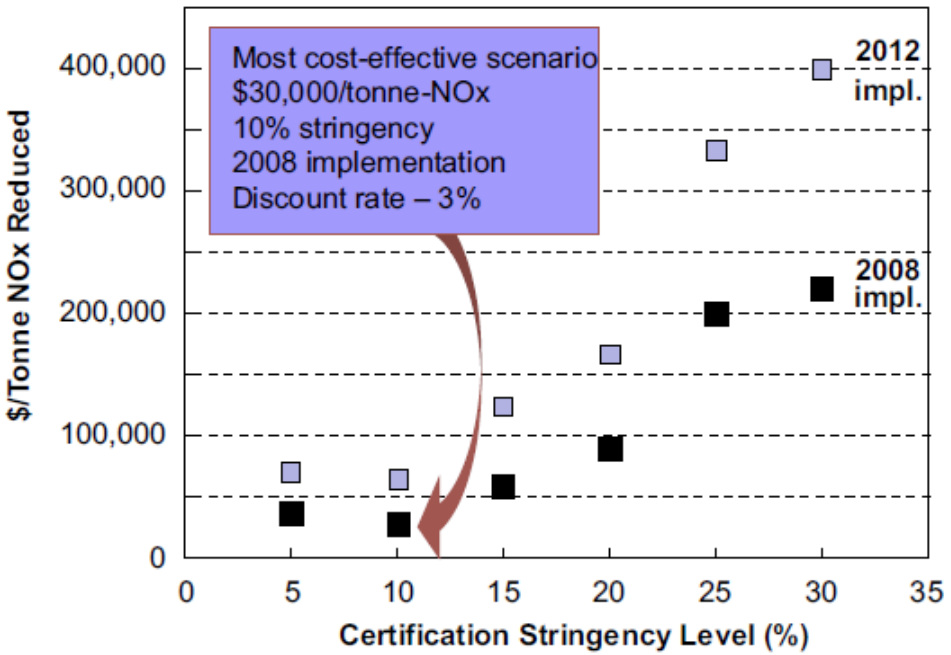
- Ensuring sustainable aviation growth will require balancing economic and environmental objectives
- Aviation benefits and environmental effects result from a complex system of interdependent technologies, operations, policies and market conditions
- Actions in one domain may produce unintended negative consequences in another
- Aviation's climate impacts are gaining importance rapidly (ICAO CO_2 Std, EU SESAR and FAA NextGen goals)

"Immediate action is required to address the interdependent challenges of aviation noise, local air quality and climate impacts."
Report to Congress – Aviation and the Environment (Dec, 2004)

Decision-making practices for aviation and environment

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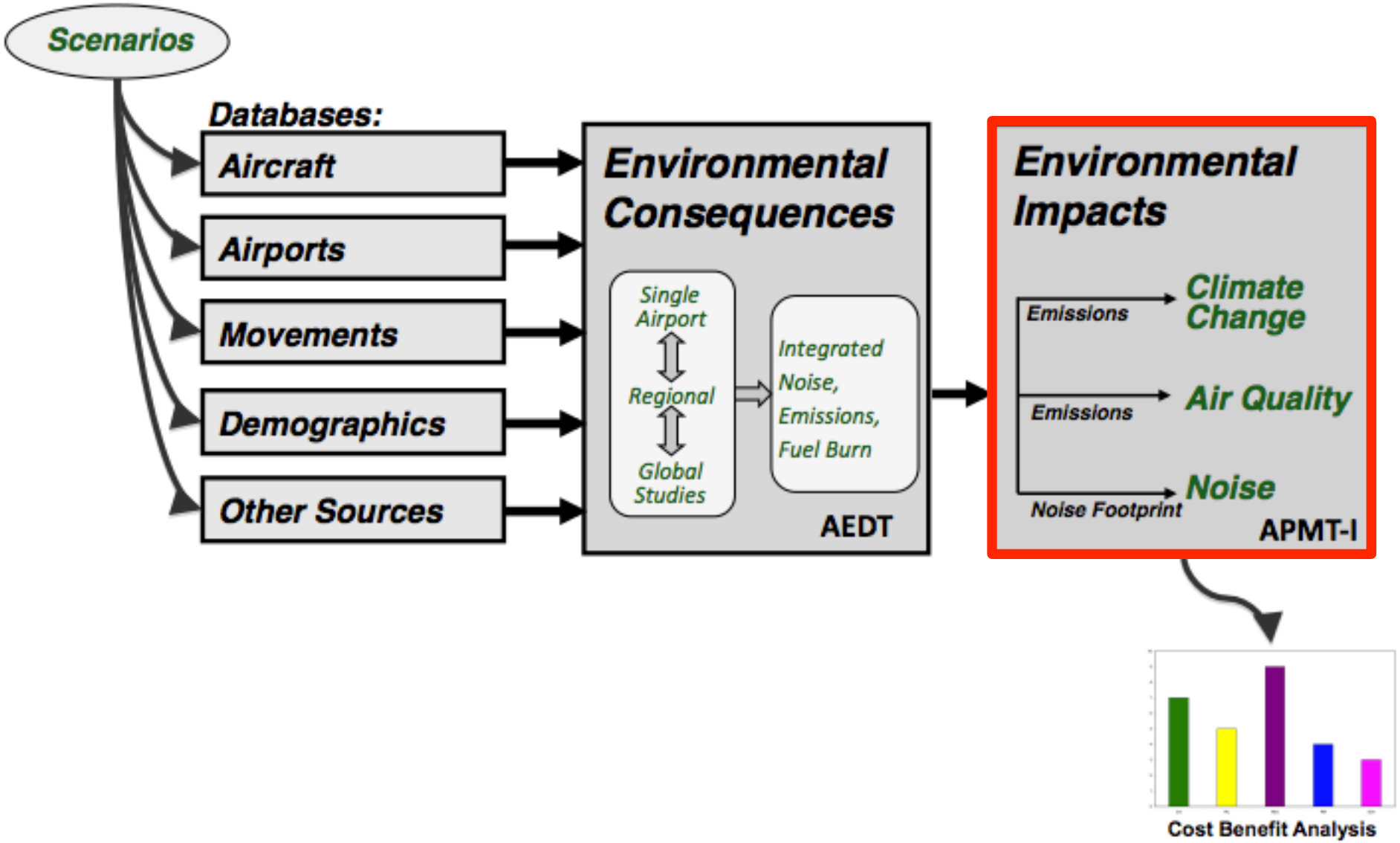
- **Assessments typically conducted independently** for climate, air quality, and noise
- **Cost-effectiveness** ($/kg NOx or $/ number of people removed from noise contour) is typical metric
- Major **shortcomings** of typical practices include
  - **Limited accounting of interdependencies among impacts**
  - **Limited treatment of uncertainties in analyses**
  - **No estimation of health and welfare impacts**
- FAA is leading the world in addressing the need for ***comprehensive analyses that address tradeoffs*** among noise, emissions and economic impacts to support decision-making
  - **Requires incorporating new and developing science, and careful accounting of uncertainties**



FESG CAEP/6-IP/13; estimates shown assume high level of manufacturers' NRC and lost fleet value, discount rate 3%

Aviation Environmental Tools Suite

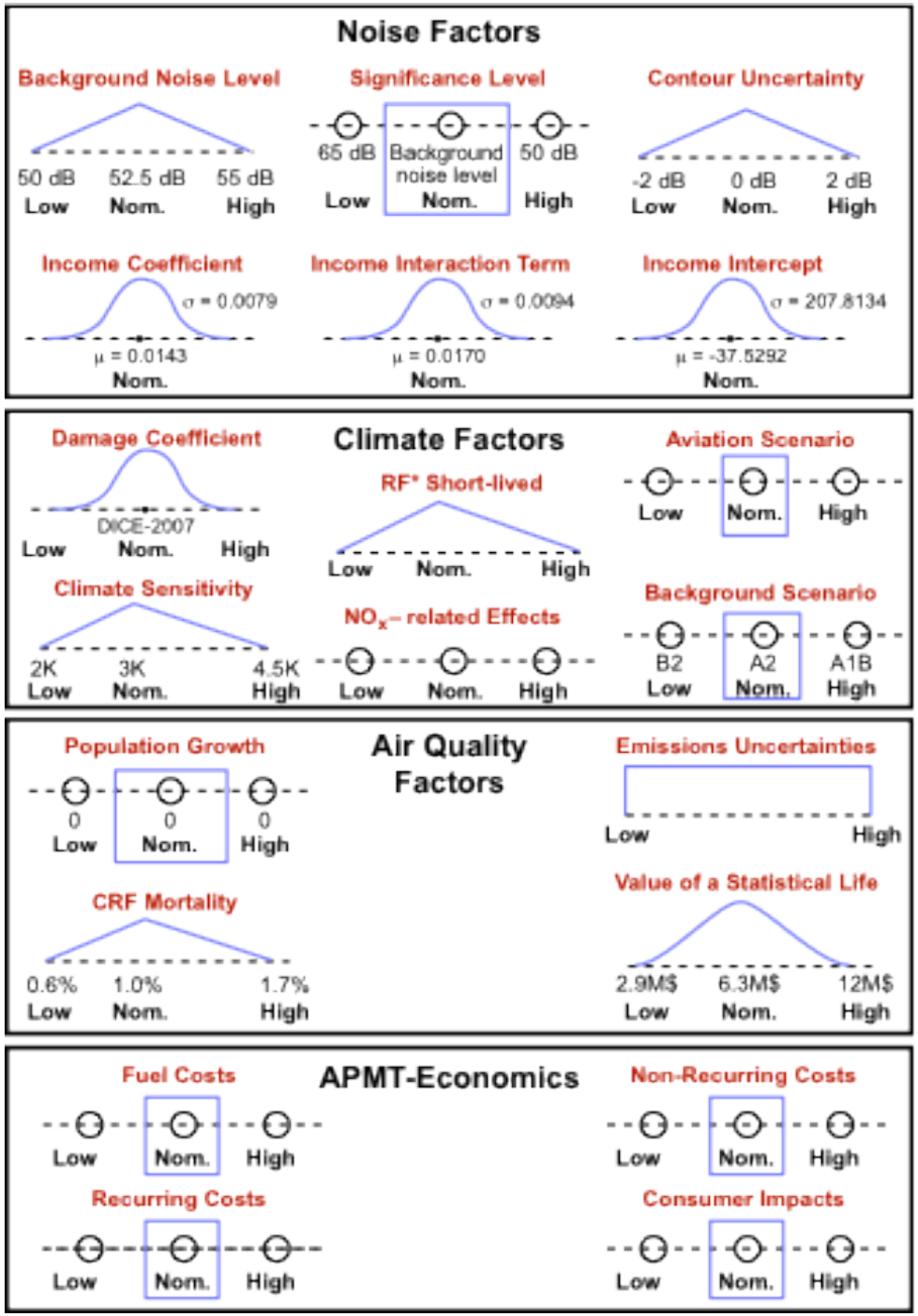
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Putting it all together is a challenge

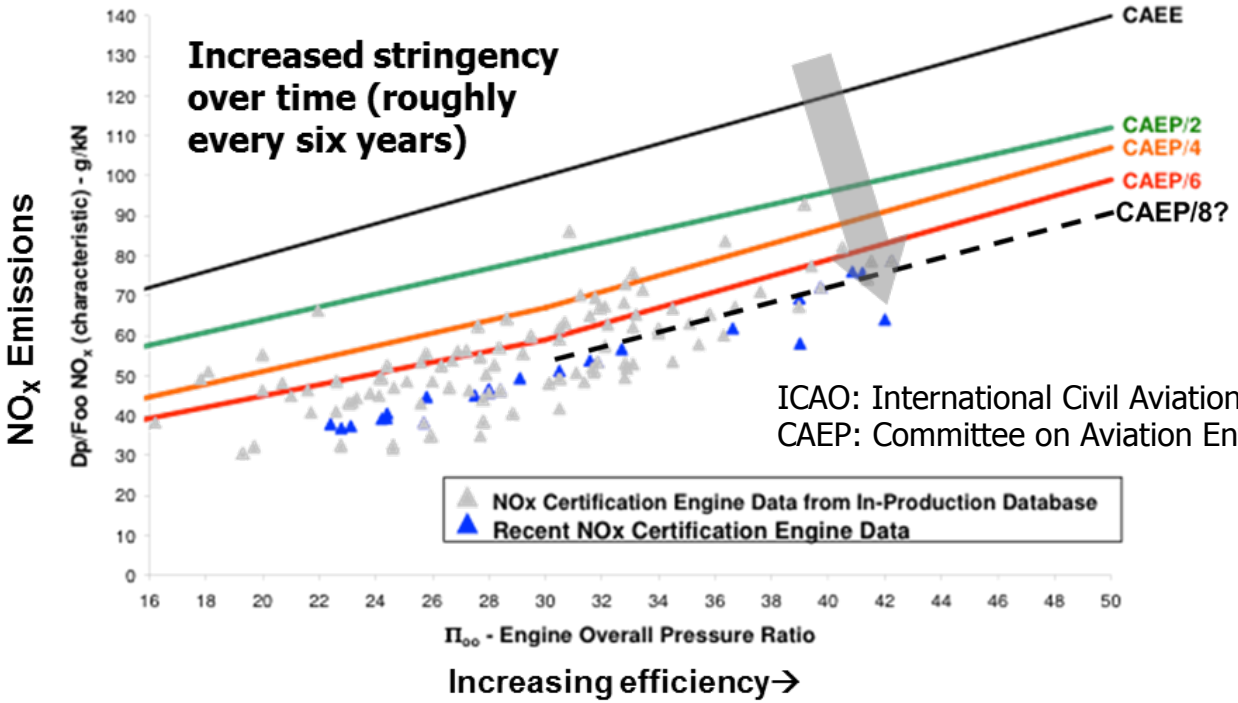
We use a range of inputs and assumptions (within probabilistic simulations)

Note: blue line signifies distribution, blue box signifies discrete value used with lens



ICAO CAEP/8 Engine NO_x emissions certification stringency

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ICAO: International Civil Aviation Organization
CAEP: Committee on Aviation Environmental Protection

- NO_x emissions (NO + NO_2) are byproducts of high pressure, high temperature combustion in jet engines
- NO_x emissions have both air quality and climate impacts
- Primary tradeoff - NO_x reductions result in a fuelburn/CO_2 penalty
- This work informed the US position for the ICAO CAEP/8 policy assessment

CAEP/8 Policy Options

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2003-2013

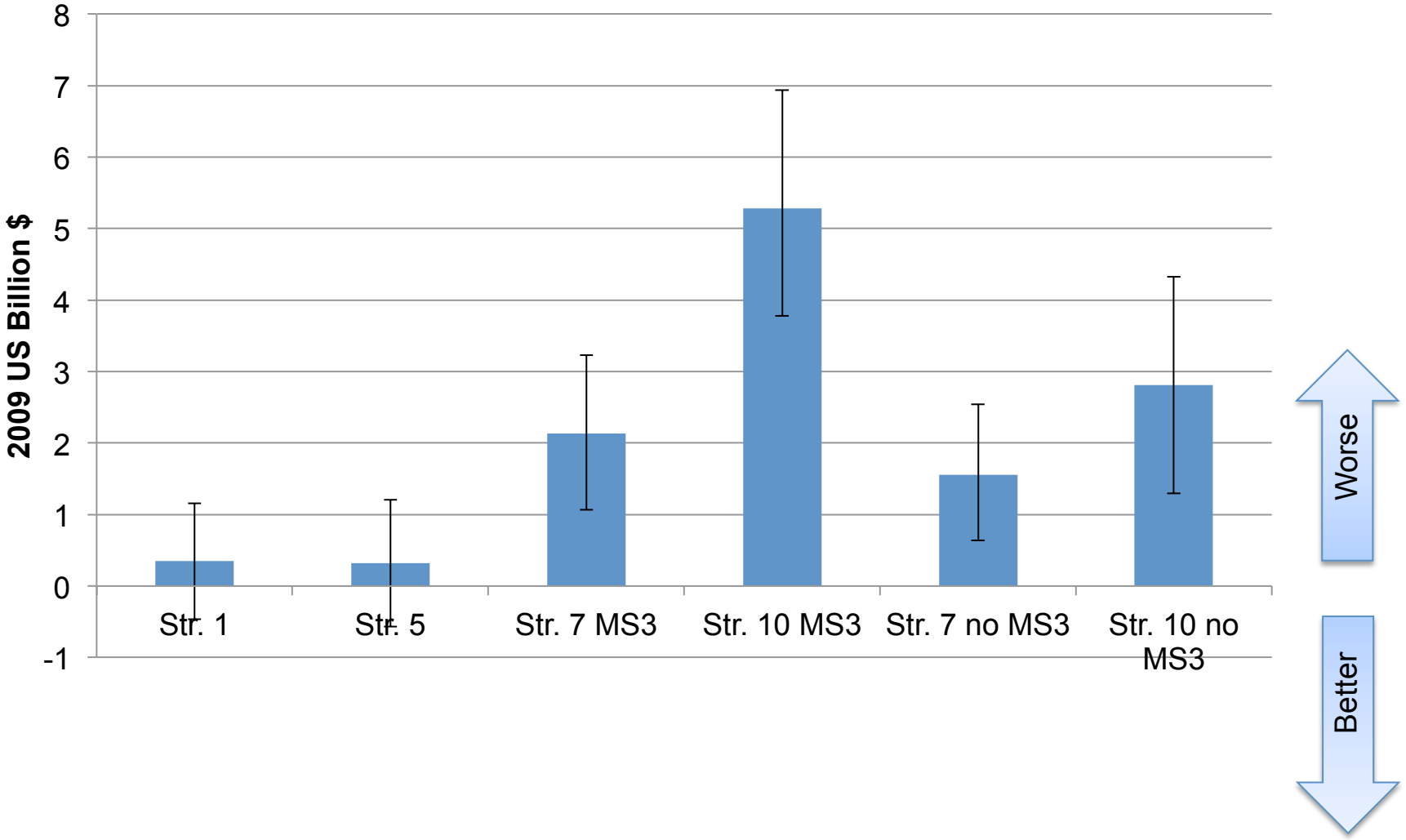
Scenario	Small Engine (26.7kN / 89kN Foo)	Large Engine	(Slope>30OPR)
1	-5% / -5%	-5%	2
2	-10% / -10%	-10%	2.2
3	-10% / -10%	-10%	2
4	-5% / -15%	-15%	2.2
5	-15% / -15%	-15%	2.2
6	-5% / -15%	-15%	2
7	-15% / -15%	-15%	2
8	-10% / -20%	-20%	2.2
9	-15% / -20%	-20%	2.2
10	-20% / -20%	-20%	2.2

Stringency 6 (the option picked by CAEP) ≈ Stringency 7 (analyzed here)

All CAEP/8 stringencies

mid-range environmental lens assumptions, US-only

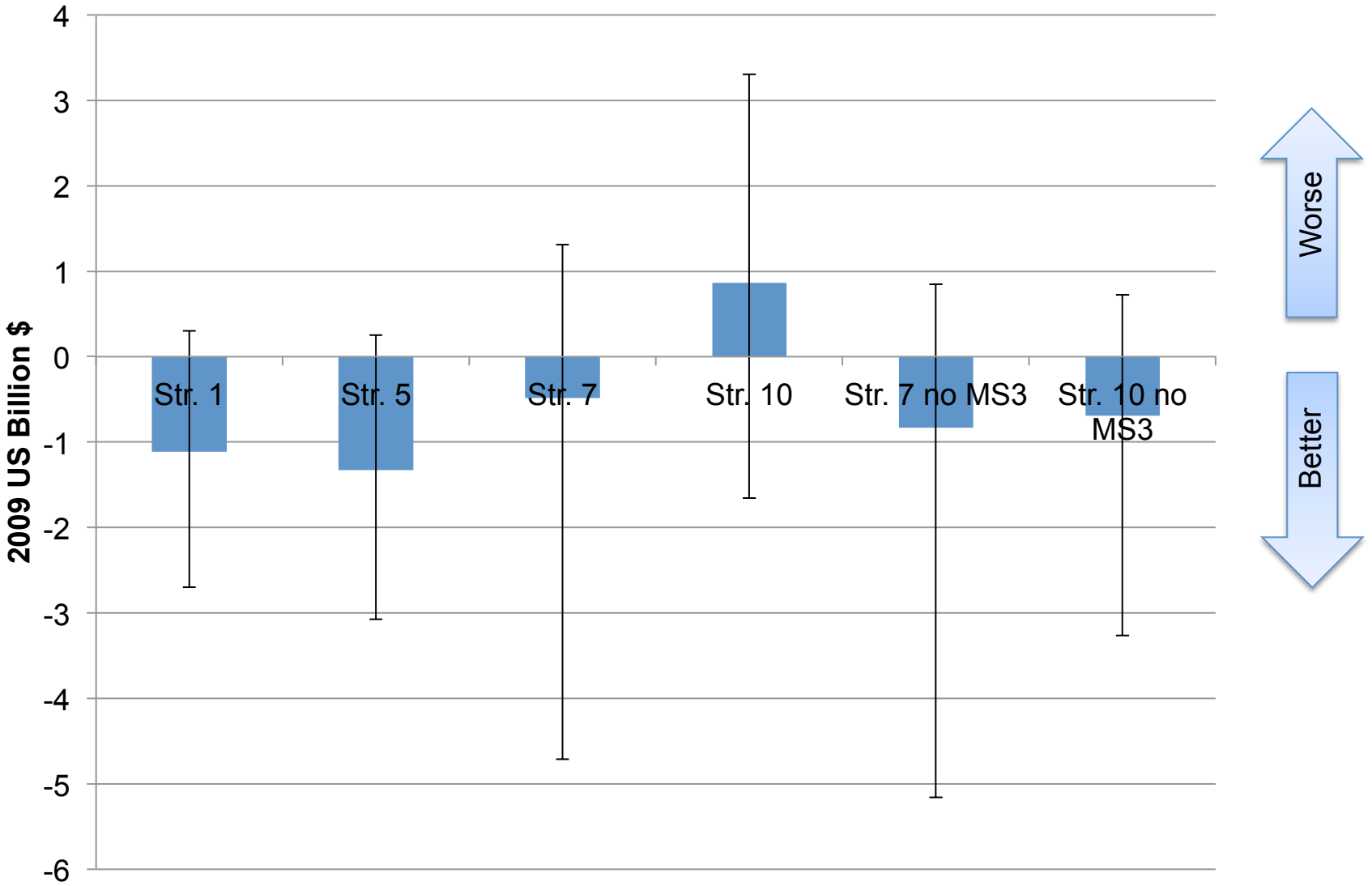
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2003-2013



All CAEP/8 stringencies

50% industry costs and 5-times air quality, US-only

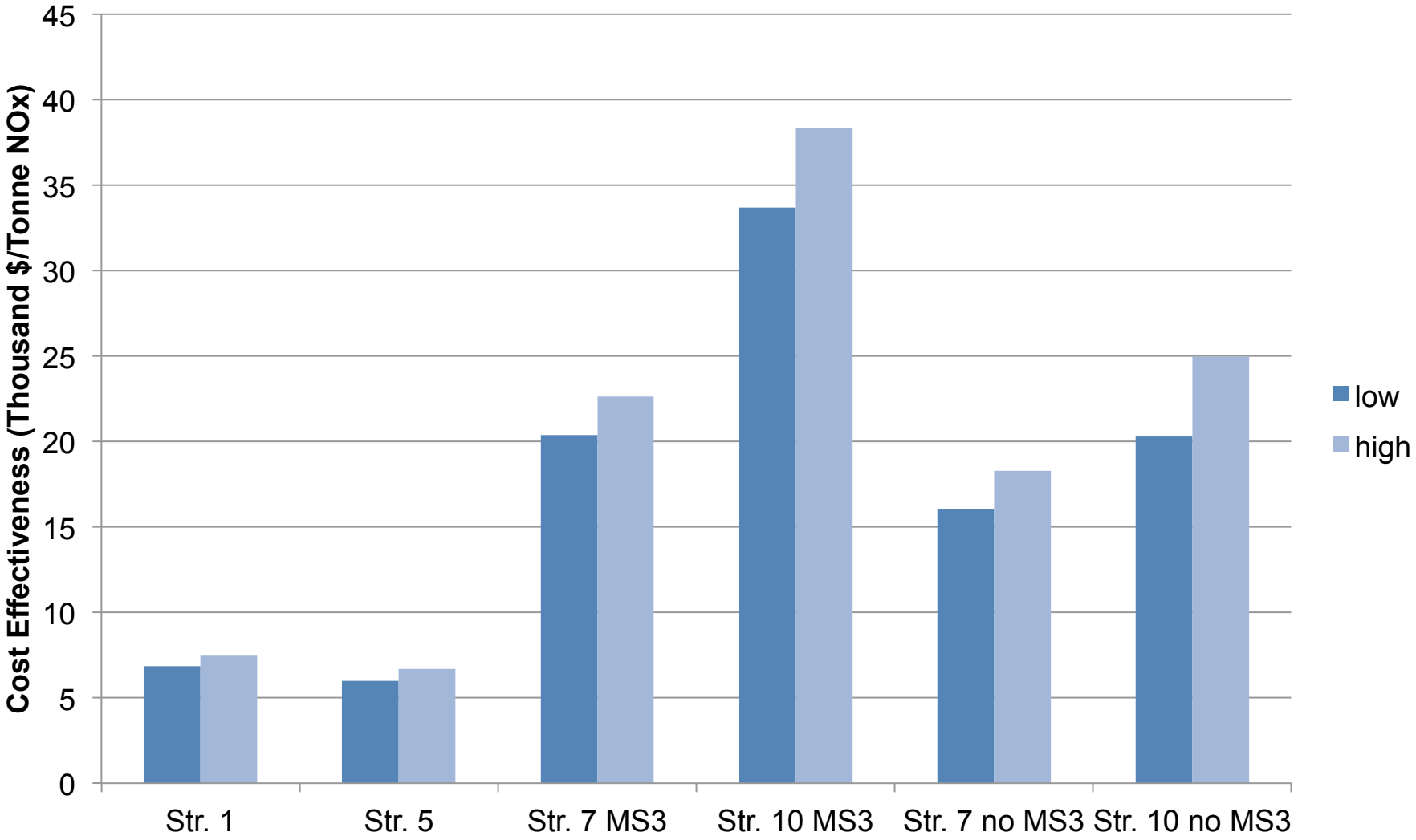
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CAEP/8 cost-effectiveness results

(c.f. CAEP/6 estimated $30K/tonne-$NO_X$-reduced as minimum)

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CAEP/8 Decision-making

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- Stringency 6 (15% for large engines)
  - similar to Stringency 7 results shown in this briefing
- "More cost-effective than CAEP/6"
- "Qualitatively supported by cost-benefit analysis"
  - 50% industry costs
  - Accounting for likely bias in AQ benefits estimates
- Aligned with political desires in both US and EU

Interfaces and Communications

CAEP/8 analysis

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2003-2013

- External
  - Key interactions with Volpe, Wyle, MVA, FAA, ICAO-CAEP Working Groups and FESG
- Publications
  - CAEP/8-IP/30: CAEP/8 NOx Stringency Cost-Benefit Analysis Demonstration Using APMT-Impacts
  - Mahashabde et al., 2010, "Assessing the environmental impacts of aircraft noise and emissions", Progress in Aerospace Sciences, Volume 47, Issue 1, January 2011
- Within PARTNER
  - Project 3: Valuation and Tradeoffs of Policy Options

Summary

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- Effects of climate, noise, and air quality are often considered separately
- Cost effectiveness is commonly used to select between potential policy options
- The purpose of this work has been to provide an integrated framework to communicate potential outcomes and uncertainties using a variety of metrics, under a variety of assumptions and scenarios
- APMT-Impacts can be used to understand the physical and monetary impacts due to policy actions and accounting for:
  - Interdependencies between climate, noise, and air quality effects
  - Uncertainties in the analysis

Contributors

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10 YEARS
2003-2013

- Professor Ian Waitz
- Maryalice Locke
- Karen Marais
- Mina Jun
- Steven Barrett
- Chelsea He
- Christoph Wollersheim
- Elza Brunelle-Yeung
- Christopher Kish
- Stephen Kuhn
- Tudor Masek
- Julien Rojo
- Aleksandra Mozdzanowska
- Alice Fan
- Akshay Ashok
- Stephen Lukachko
- Philip Wolfe

Welcome back!



10th Year Public Symposium
March 1, 2013
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PARTNER RESEARCH, 2003 – 2013

PUBLIC SYMPOSIUM

AIRCRAFT TECHNOLOGY

Session Chair: Steven Barrett

Opinions, findings, conclusions and recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of PARTNER sponsor organizations.

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AIRCRAFT TECHNOLOGY

Technology modeling and assessment tools

Presented by:
Dr. Michelle Kirby, GT

Opinions, findings, conclusions and recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of PARTNER sponsor organizations.

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Environmental Modeling Challenges

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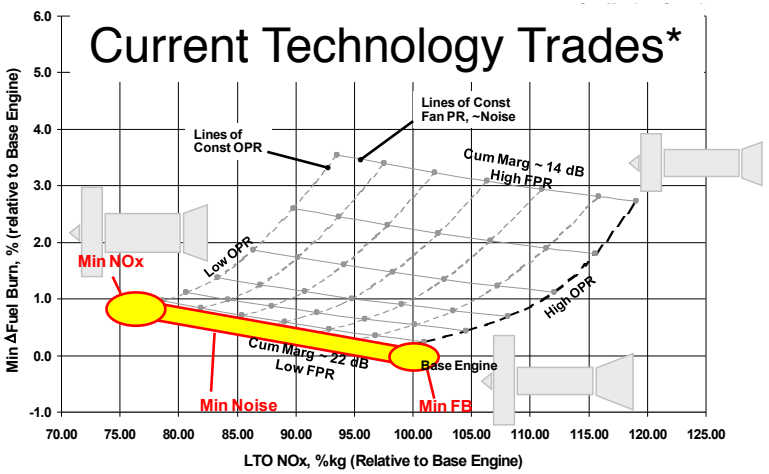
- Physics drive the environmental trade-offs and their interdependencies
- Need a means to understand interdependencies for existing and future classes of vehicles
- Emphasis is not designing aircraft and engines, but on trends and correlations
- Move beyond frozen technology inventories currently being used
- Study initiated by Air Transport Association (now A4A) and Aerospace Industries Association (Manufacturers) focus to define an "Environmental Design Space" that*:
  - Quantifies Engine/Airplane design trade-offs in a manner that is technically feasible
  - To support environmental regulatory discussions
  - Provide guidance for certification standards process
- Questions:
  - What does an "Environmental Design Space (EDS)" look like for current and future aircraft/engine systems?
  - What are the tradeoffs in terms of performance, noise, and emissions for technically feasible aircraft/engine systems?

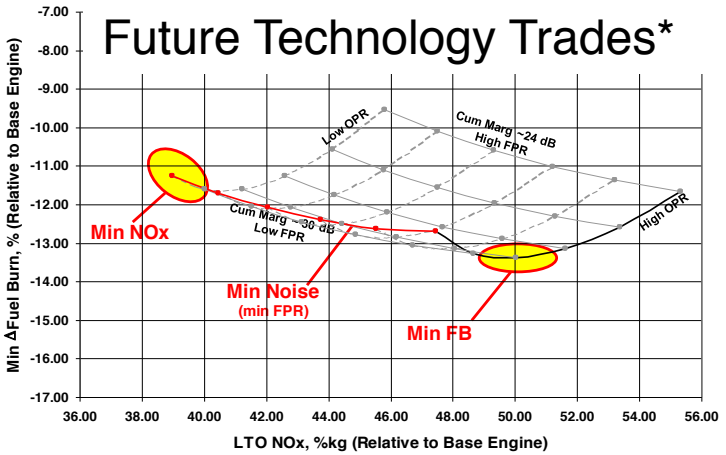
* Source: 2003: "*Environmental Tradeoffs in Commercial Aircraft Design: AIA EDS Feasibility Test and Lessons Learned*" Dave Halstead, GEAE

Foundation for Environmental Modeling Capabilities

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- Quantifying environmental impact is a complex, multi-disciplinary, systems-based problem
- Significant environmental trades occur…
  - Best Noise solution is not best NO_x solution is not best CO_2 (ie, fuel burn) solution
- An integrated approach is key to attaining balanced environmental regulatory strategy
  - Noise vs. CO_2 vs. NO_x
  - Local vs. national vs. global impact
  - Implications to costs and benefits to achieve a balanced solution



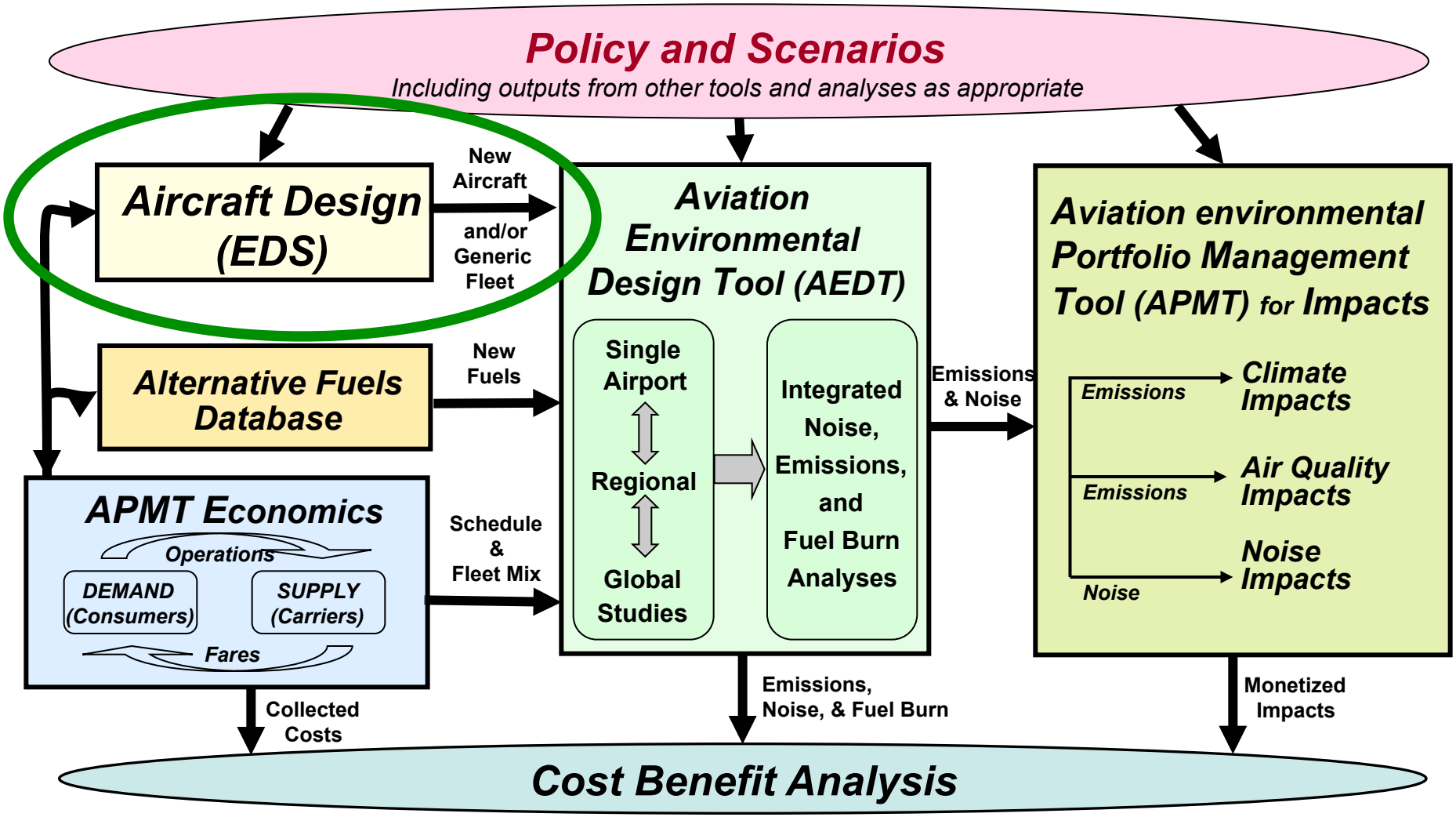


The FAA took the initiative to pursue the development of a tool suite to address these needs

* Source: 2003: "*Environmental Tradeoffs in Commercial Aircraft Design: AIA EDS Feasibility Test and Lessons Learned*" Dave Halstead, GEAE

FAA Aviation Environmental Tool Suite

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EDS Research Objectives

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- Be capable of analyzing the environmental and economic effects of:
  - New Technologies
  - New Aircraft both replacement and new system types
- Methods and assumptions must be non-proprietary and data generated must be accessible to the international community to increase transparency
- Enable the exploration of trade-offs and interdependencies amongst and between technology, economics and environmental impacts at the aircraft level
- Must be compatible with the other tools in the FAA Tool Suite
- Educate the next generation of engineers
- Actively engage industry and government experts to ensure valid trade-spaces and trends of NO_x vs. Noise vs. CO_2

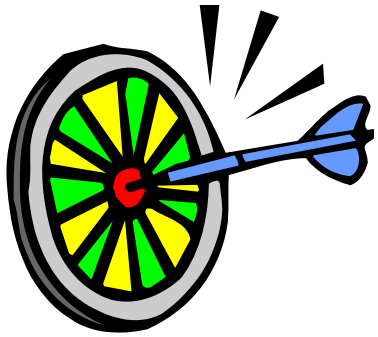
What is the Environmental Design Space (EDS)?

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2003-2013

- Aircraft modeling and simulation environment developed by Georgia Tech with funding from FAA, NASA, and Transport Canada
- Develops physics-based models using NASA tools: CMPGEN, NPSS, WATE++, FLOPS, and ANOPP
- Allows a more comprehensive assessment of the noise and emissions impacts of aviation to inform national and international decision makers
- Provides a means to understand interdependencies of existing and future classes of vehicles based on realistic and accepted industry design philosophies
- Capable of passing vehicle characteristics to other elements of FAA tool suite, such as the Aviation Environmental Design Tool (AEDT), for a full global assessment of aviation impacts

EDS: Vehicle focused analysis





- One of the primary objectives of EDS is to enable the exploration of trade-offs and interdependencies amongst and between technologies and environmental impacts at the aircraft level
- More detail, hitting the target, and accuracy are important!
- Use surrogate models to explore technology solutions
- Actively engage industry and government experts to ensure high quality results

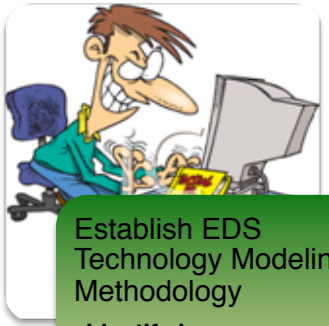
Technology Modeling Process

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2003-2013



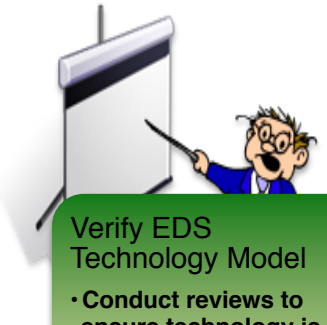
Research Technology

- **Conduct Literature Review**
- **Identify Interdependencies**



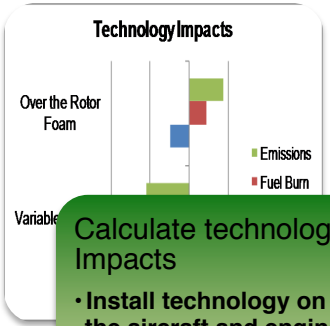
Establish EDS Technology Modeling Methodology

- **Identify how technology works**
- **Establish modeling routine**
- **Implement in EDS**



Verify EDS Technology Model

- **Conduct reviews to ensure technology is modeled correctly**



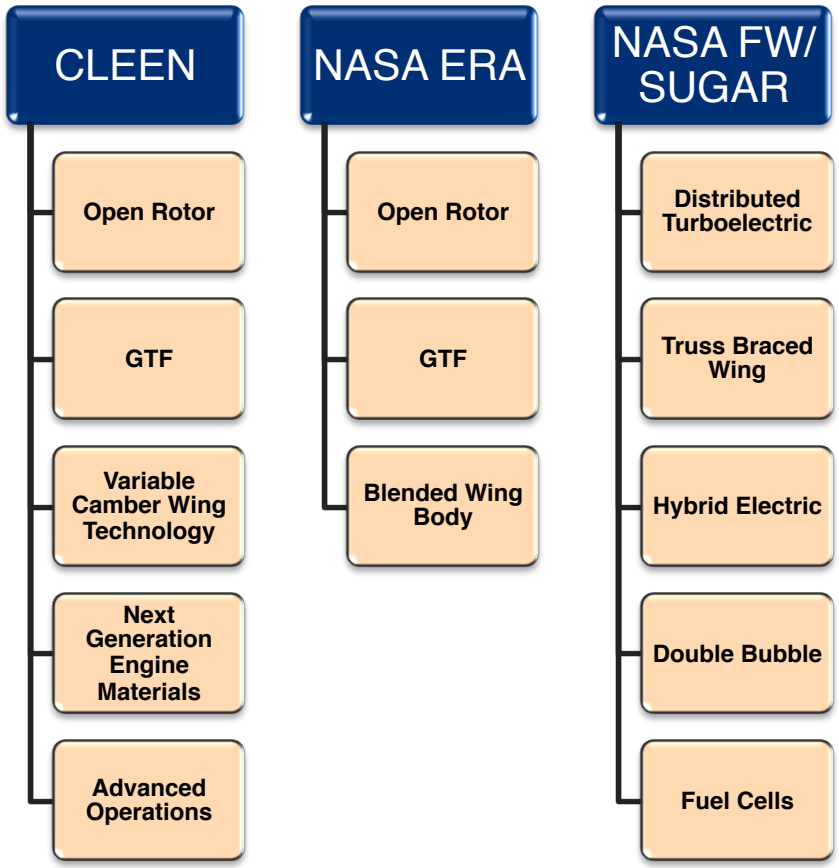
Calculate technology Impacts

- **Install technology on the aircraft and engine to determine effect on fuel burn, noise, and emissions**

Leveraging Advanced Technology Modeling

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10 YEARS
2003-2013

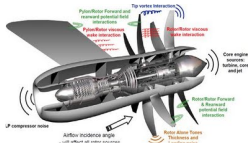
- EDS base capability is continually enhanced through both FAA and NASA research programs
  - Allows EDS to be continually improved and refined
  - Having many stakeholders means EDS is **continually vetted**; formally and informally
  - Allows government agencies to share development costs and benefits



EDS Capabilities and Value

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- Years of V&V of predictive capability through the IRG and NASA systems analyst and SME input
- AEDT seamless connectivity
- Extensive library of aircraft configurations, including advanced configurations
  - Large library of engine/airframe architectures from existing to N+3 aircraft types





- Multi-level fidelity with a plug and play framework
- Realistic interdependency capability for current and future aircraft types:
  - Cost estimations
  - In-line noise estimation
  - CO2 (fuel burn), NOx, and noise
- Dynamic tool with continuous evolution of capability through industry and government SME input and a large team of disciplinary experts at GT
- Common tool for all commercial US R&D programs
  - Modeled CLEEN, NASA N+2, and NASA N+3 vehicles within FAA EDS or NASA specific versions of EDS to incorporate higher fidelity tools

"[EDS is] the best simulation of engines and airplanes outside of the companies that make them."

- Jeff Berton, NASA Glenn Research Center

Fleet Modeling Capabilities and Value

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10 YEARS
2003-2013

- GREAT:
  - Fleet-wide screening tool capability to rapidly investigate policy or technology investment strategies at the system level
  - Extensive V&V with FAA and Volpe SMEs
  - Consistent with AEDT results with future fleet evolution consisting of the generic fleet
  - Parametric capability to test fleet assumptions
- ANGIM:
  - Framework to rapidly calculate fleet-wide noise impacts based on EDS and GREAT inputs
- EDS → GREAT → ANGIM → AEDT → APMT-I
  - Seamless integration capability

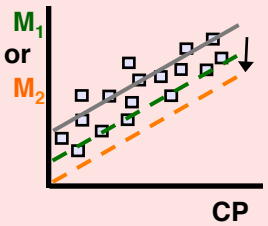
"EDS has been a key element supporting NASA's Environmentally Responsible Aviation project, providing system level benefit assessments for a wide variety of technologies and configurations."

- Craig Nickol, NASA Langley Research Center

Assessment of Fleet-wide Environmental Impacts

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10 YEARS
2003-2013

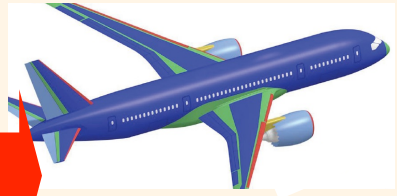
Standards (CO_2, NO_x, or noise)

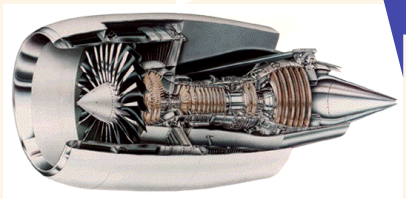


- Metric
- Correlation Parameter
- Evaluation Option
- Applicability
- Implementation Date

EDS

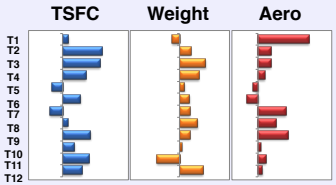
Generic Vehicles



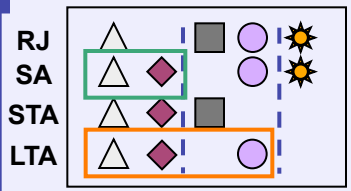


Technologies

- Benefit
- Cost
- Applicability
- Availability



Technology Roadmaps



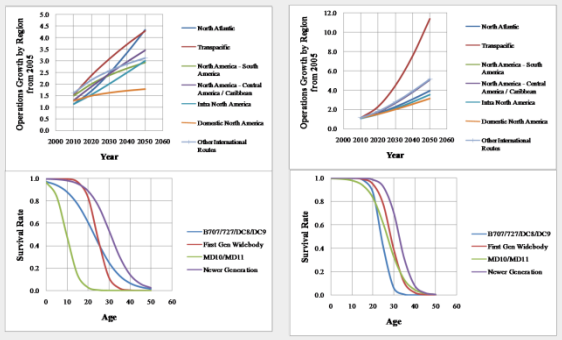
Scenarios

Scenario 1
Scenario 2
⋮

Vehicle Performance Characteristics

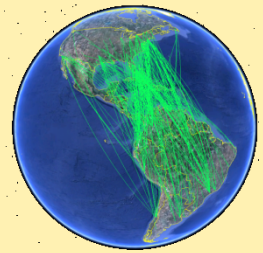
Operations

- Demand Forecast
- Aircraft Retirements
- Replacements Schedule

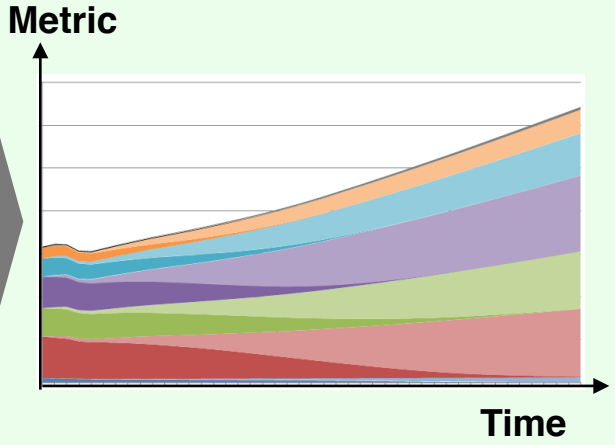


AEDT or GREAT

Fleet Analysis



Fleet Impact



Key Applications

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10 YEARS
2003-2013





	EDS Vehicle Anaysis	GREAT Fleet Analysis	ANGIM Noise Analysis
CAEP CO2	✓	✓	✓
CLEEN	✓	✓	✓
JPDO	✓		
NASA ERA	✓	✓	✓
NASA FW	✓	✓	
PARTNER P30	✓	✓	✓
PARTNER P43	✓	✓	✓
US EPA	✓	✓	
US FAA NextGen	✓	✓	✓





"EDS allowed for some very useful testing in development of the ICAO CO_2 metric [system]. It allowed quantitative investigations of how the candidate metrics responded to various airplane design parameters."

- Mike Garrison, Boeing

Recognizing EDS and Team Application Accomplishments

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10 YEARS
2003-2013

- "**The EDS model has proven invaluable** for projecting and assessing aviation environmental technology insertion and resulting environmental benefits and potential tradeoffs. It has been **critical** in environmental **goal setting**, advancing our understanding of how to **effectively implement NextGen** and in the assessment of **new environmental certification standards** for aircraft, including providing backbone analyses to support the development of an aircraft CO_2 standard. The **rigor of the tool** and of the **Georgia Tech experts** in employing it have greatly advanced aviation environmental protection."
  - *Nancy N. Young, Vice President, Environmental Affairs, Airlines for America*
- "Dr. Michelle Kirby and her team at Georgia Tech have been **major contributors** to the work of ICAO's Committee on Aviation Environmental Protection (CAEP) **to develop a CO_2 Certification Standard** for gas turbine and turbo-prop powered aircraft. Application of the **EDS tool has contributed greatly** in advancing the development of a certification metric and in providing valuable insight into the environmental trade-offs that must be addressed in developing the final Certification Standard"
  - *Dom Sepulveda, Manager - Environmental Regulatory Affairs – Emissions, Pratt & Whitney*
- "**NASA** ERA continues to **rely upon EDS** to study and quantify the potential "environmental-based" impacts of promising technology at the aircraft system level and at the fleet level, for current and future aircraft configurations. I have heard it said that flight experiments separate the real from the imagined. I believe thorough **systems studies using EDS has allowed NASA to differentiate realism from excessive optimism** as we perform due diligence in [the] development of efficient research portfolios that have the greatest positive impacts on both the environment and aircraft performance.
  - *Dr. Fayette Collier- Manager, Environmentally Responsible Aviation (ERA) Project , NASA*

What impact has PARTNER made to educating students?

PARTNER
10 YEARS
2003-2013

- One key tenet of the EDS program and also PARTNER was to educate the next generation of engineers
- Since EDS began at GT in 2006, the following have been supported:
  - More than 90 MS and PhD students
  - More than 30 undergraduate students
- Many of the students have gone on to work with a permanent position for one of the PARTNER AB members, including:
  - Airbus, Boeing, Delta, FAA, GE, IATA, Lockheed Martin, Mitre, NASA, Pratt & Whitney, Rolls Royce

"The students were continuously exposed to experienced aviation professionals to gain knowledge and insight to research methods and practices, **and** the professionals learned from the students in terms of out of the box thinking."

- Mayor Arlene Mulder, O'Hare NCC

Interfaces and Communications Through the Years

PARTNER
10 YEARS
2003-2013

- External
  - CAEP
  - A4A, IATA, ICCAIA members
  - DLR
  - NLR
  - QinetiQ
  - Booz Allen Hamilton
- Within PARTNER
  - AEDT and APMT-E development teams
  - FAA, MIT, NASA, Volpe, Wyle
  - Project 2, Project 30, Project 35, Project 36, Project 43
- Publications:
  - Numerous conference papers, 14 Ph.D. thesis, and CAEP papers resulted from the EDS program development and application

Summary

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10 YEARS
2003-2013

- Continued development of core capabilities of EDS to support various analyses at various levels of fidelity through active engagement of industry and government experts
- Developed a very capable vehicle analysis tool to address the needs of assessing interdependencies at the vehicle level under various analysis scenarios
- Created the linkages to all the other FAA Tool Suite capabilities so as to enable a full execution of all the tools to enable more informed policy decision making with technology advancements
- Developed a capability to assess numerous fleet-wide scenarios with reduced computational effort as a screening tool
- Provides the common framework for all U.S. aeronautical R&D portfolio analysis (FAA and NASA)
- Trained the next generation of engineers with relevant research and engagement with experts
- EDS is the state of the art in aircraft/engine design

Current Contributors

PARTNER
10 YEARS
2003-2013

- Staff:
  - Prof. Dimitri Mavris (PI), Dr. Michelle R. Kirby (Co-PI), Dr. Taewoo Nam (Chief Engineer), Dr. Holger Pfaender, Dr. Dongwook Lim, Dr. Elena Garcia, Dr. Brian Kestner, Dr. Leihong Li, Dr. Yongchang Li, Chris Perullo, Graham Burdette, Ben Havrilesko
- Graduate Students:
  - Jose Bernardo, Matthew Levine, Andrew Flett, Jeroen Geeraert, Lynn Huynh, Jordan Mellen, Andrew Peterson, Abhay Kaul, Imon Chakraborty, Fabien Grisaud, Clark Kjorlaug, Will Whittcar, Ludovic Hivin
- Undergraduate Students:
  - Kyle Davis

PARTNER RESEARCH, 2003 – 2013

PUBLIC SYMPOSIUM

AIRCRAFT TECHNOLOGY

Assessment of metrics for an Aviation CO_2 Certification Standard

Presented by:
Dr. Michelle Kirby, GT and
Dr. Philippe A. Bonnefoy, Booz Allen Hamilton

Opinions, findings, conclusions and recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of PARTNER sponsor organizations.

10th Year Public Symposium
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PARTNER
Partnership for Air Transportation Noise and Emissions Reduction

Motivation: Need to Mitigate CO2 Emissions

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2003-2013


2

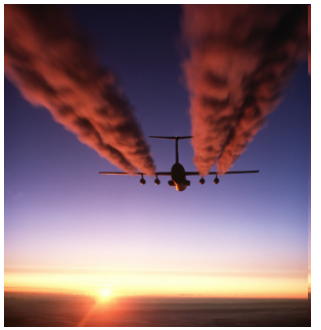
- Increasing concern over global climate change due to anthropogenic greenhouse gas emission (GHG)
- Carbon Dioxide (CO_2) one of the most important greenhouse gases[1]
  - Prevalent from energy, transportation, industry, agriculture, commercial, and residential sources
  - Direct climate effect through absorption and reemission of infrared radiation
  - Emission affects earth climate for centuries
- Need to mitigate CO_2 emissions in the future
- Ambitious goals set for U.S. (e.g. carbon neutral growth by 2020 w/ 2005 baseline)

1 Wuebbles D., "Workshop on the impacts of aviation on climate change: a report of findings and recommendations", PARTNER-COE-2006-004, 2006.
2 http://mattbenchener.files.wordpress.com/2009/06/cap-and-trade.jpg

Mitigating Aviation's Contribution to CO_2 Emissions

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10 YEARS
2003-2013

- Increasing concern over aviation's contribution to climate change
  - Commercial aircraft contribution to domestic GHG emissions rather small: ~2%[1]
  - Contribution to climate change estimated to be higher[2]
  - Aviation demand expected to increase over the upcoming decades
- Several solutions available to mitigate aviation's environmental impacts
  - Aircraft Technologies
  - Operational Improvements
  - Alternative Fuels
  - Policies



5

- Top priority for current ICAO/CAEP[3] work is CO_2 standard[4]

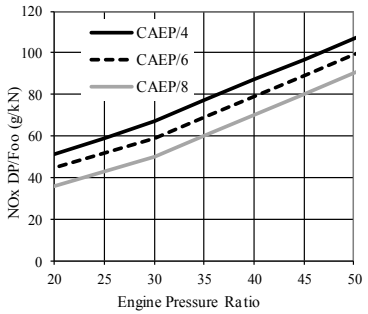
Research Goal: Identify and comprehensively assess candidate metrics for a commercial aircraft CO_2 certification standard

1 US GHG Inventory 2010, US EPA, 2010
2 Clearing the Air: The Myth and Reality of Aviation and Climate Change
3 International Civil Aviation Organization www.icao.int
4 CAEP/8 WP80 Agenda Item 5
5 http://www.eu2008.fr

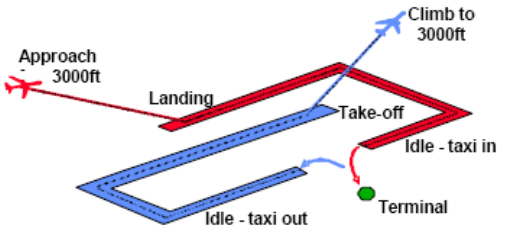
Background: Global Environmental Standards

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2003-2013

NOx Standard

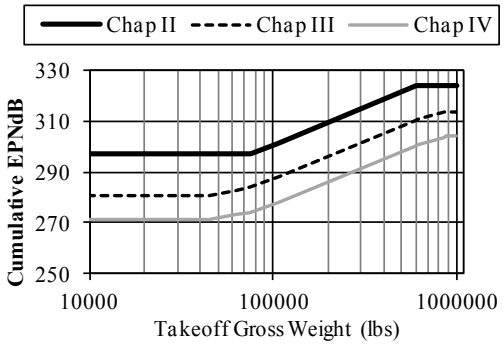


Representative Emissions LTO Cycle

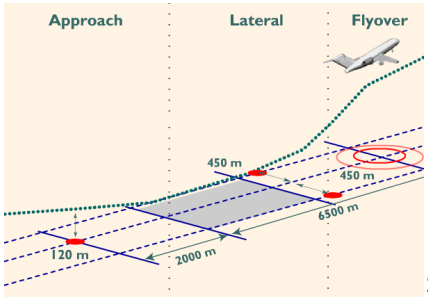


1

Noise Standard

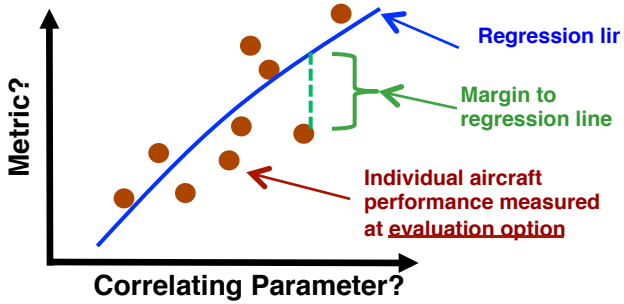


Representative Noise Certification Locations

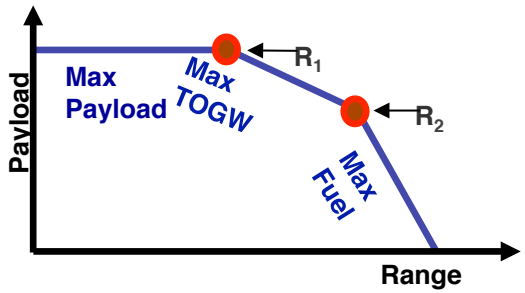


2

Future CO_2 Standard



Notional Aircraft Payload-Range Chart



1 Aircraft engine emissions certification - a review of the development of ICAO Annex 16, Volume II (EC-NEPAir)
2 http://noisedb.stac.aviation-civile.gouv.fr/

Objective of Standard

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10 YEARS
2003-2013

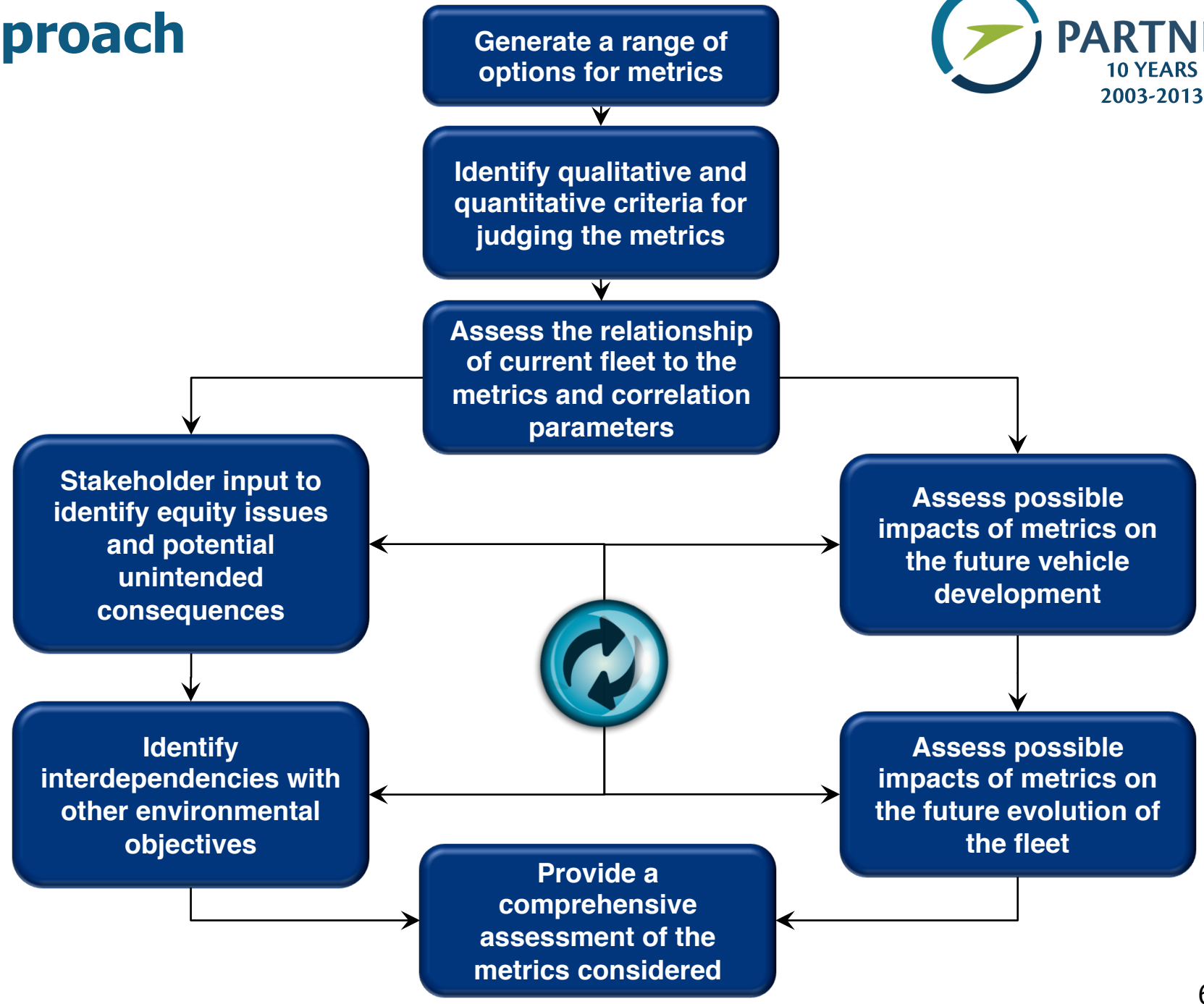
- Incentivize the reduction of CO_2 emissions beyond what can be achieved under normal market forces

- Standard should only incentivize introduction of fuel burn reduction technologies

- Standard should not discriminate based on how the aircraft is operated

Approach

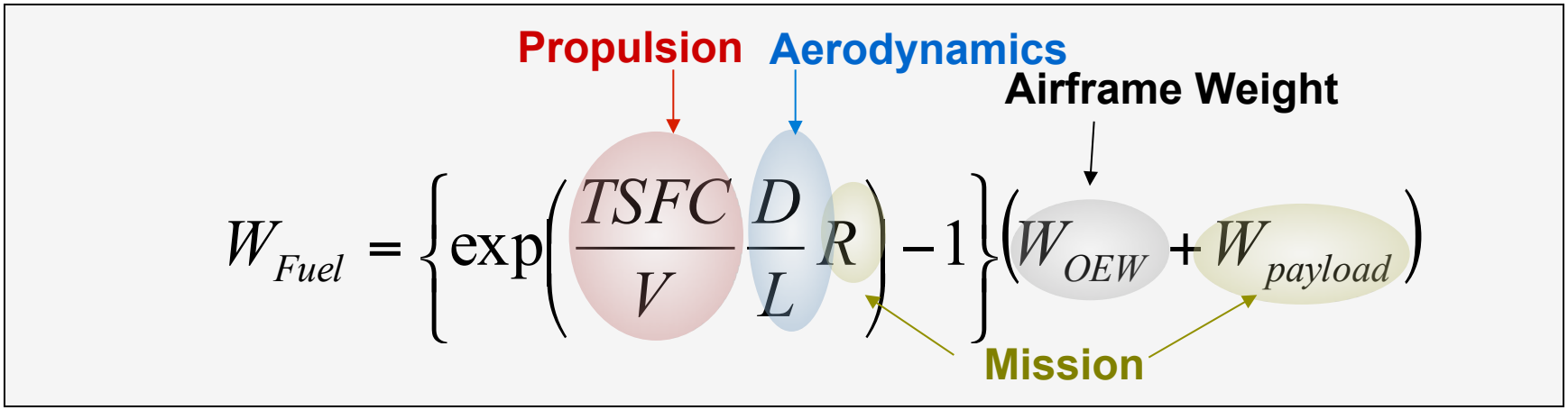
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2003-2013



Fuel Efficiency Fundamentals

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2003-2013

- Primary environmental issue is the emission of CO_2
- CO_2 emissions are proportional to fuel burn
- Drivers of CO_2 can be determined at aircraft-level



Fuel burn is driven by:

- Technology:
  - Propulsion,
  - Aerodynamics, and
  - Airframe weight (Structural Efficiency)
- Mission:
  - Payload
  - Range

Foundation of CO_2 Emission Metrics

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2003-2013

- Two major metric system types investigated: instantaneous (1/SAR) and full mission fuel

1/SAR Instantaneous Performance Measure	Mission Fuel Mission Performance Measure
• Requires a small number of parameters to specify measurement condition ○ Weight ○ Atmospheric conditions ○ Altitude ○ Speed	• Requires a standard mission profile(s) that includes all specifics required to compute fuel burn for each mission segment • Larger number of parameters needed to evaluate • Would require a generalized full mission definition across all aircraft types • Explicitly captures all phases of flight

$$1/SAR = \frac{dW_f}{-dR} = \frac{Fuel\ Flow}{V} \quad \text{measured in} \quad \frac{\text{kg}}{\text{km}}$$

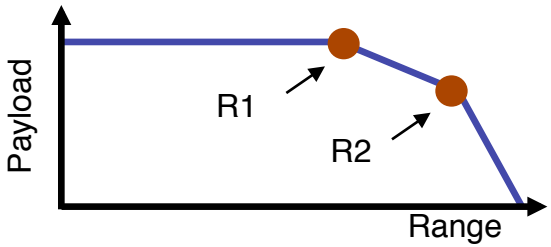
- 1/SAR is simpler than mission fuel, lessening the burden on certification authorities
- 1/SAR captures fundamental aircraft fuel efficiency parameters but it is a single cruise point, not a full mission

Candidate Metrics

PARTNER
10 YEARS
2003-2013

- Identified by several methods
  - Analytically
  - Proxy or substitution of productivity parameters
  - Literature or external recommendation
- Have similar general form
  - Relate fuel consumed to useful work produced
  - Represent two categories of conditions
    - Instantaneous
    - Entire mission

Mission or block fuel typically measured in relation to payload & range capabilities



SAR typically measured as % Maximum Take-Off Weight (MTOW)

Sample of Candidate Metrics

Instantaneous Performance

$$\frac{\text{Fuel}}{\text{Distance}}$$

1/ SAR
SAR: Specific Air Range

Entire Mission (Block) Performance

$$\frac{\text{Block Fuel}}{\text{Range}} \qquad \frac{\text{Block Fuel}}{\text{Payload} * \text{Range}} \qquad \frac{\text{Block Fuel}}{\text{Max Useful Load} * \text{Range}}$$

$$\frac{\text{Block Fuel}}{\text{MTOW} * \text{Range}} \qquad \frac{\text{Block Fuel}}{\text{Floor Area} * \text{Range}} \qquad \frac{\text{Block Fuel}}{\text{Seats} * \text{Range}}$$

Metric System Evaluation Criteria*

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2003-2013

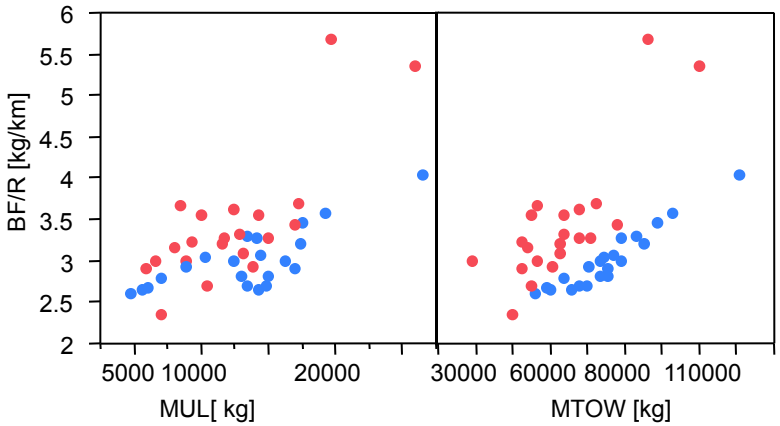
EC #	Description
1.1	The certification standard must not compromise safety levels
1.2	The CO_2 certification requirement should be aeroplane performance based, should reflect CO_2 emissions at the aeroplane level
1.3	**Should differentiate products with different generations of CO_2 reduction technologies**
1.4	**Should aim to be independent of aeroplane purpose or utilization**
1.5	Should decouple effects of fuel performance from aeroplane performance
2.1	**Should correlate with a reduction of CO_2 emissions at the aeroplane level as demonstrated by procedures which are relevant to day to day operations**
2.2	Should take into account fundamental aeroplane design elements and capabilities
3.1	Should be objective and needs to be based on certified aeroplane parameters and/or currently non-certified parameters, Parameters should be already certified or easy to measure
3.2	Should consider the industry standard practices of measurement and adjustment
4.1	Should be robust against unintended consequences
4.2	Limit interdependencies with other standards
4.3	**To the extent practicable, the certification requirement should be fair across the set of stakeholders, such as manufacturers and operators**
5.1	The certification requirement should not require an inappropriate level of resources on the part of National Airworthiness Authorities and manufacturers to implement.
6.1	Should be explainable to the general public

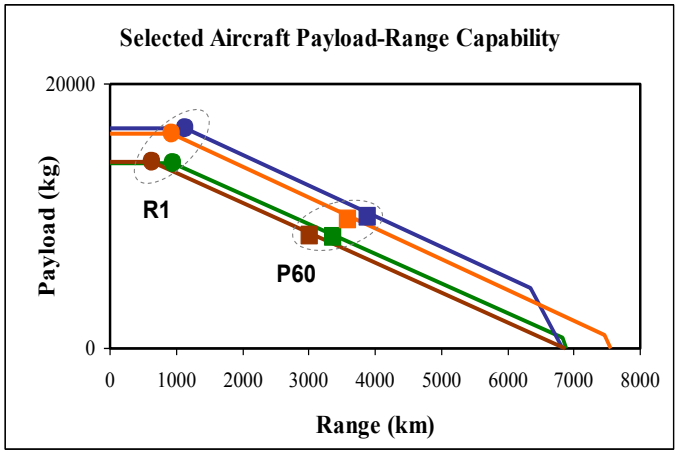
** Evaluation criteria in green could be tested quantitatively*

Need for a Metric System Assessment

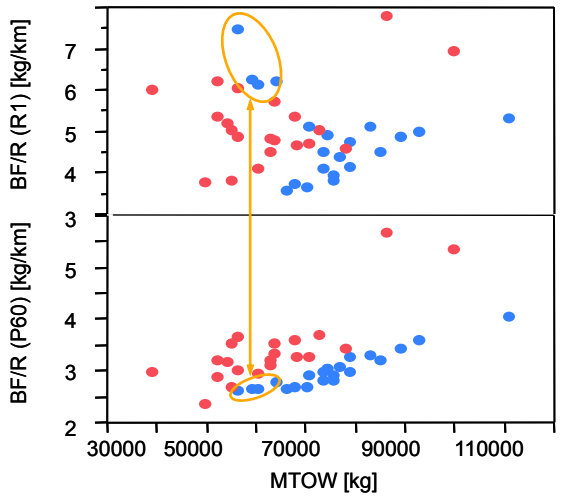
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2003-2013

- Choice of Correlating Parameters (CP) can substantially impact behavior of metric with respect to Evaluation Criteria (EC)
- Evaluation Option also significantly influences behavior of metric with respect to EC





A metric, CP, and evaluation option must be considered concurrently when evaluating performance against the ECs



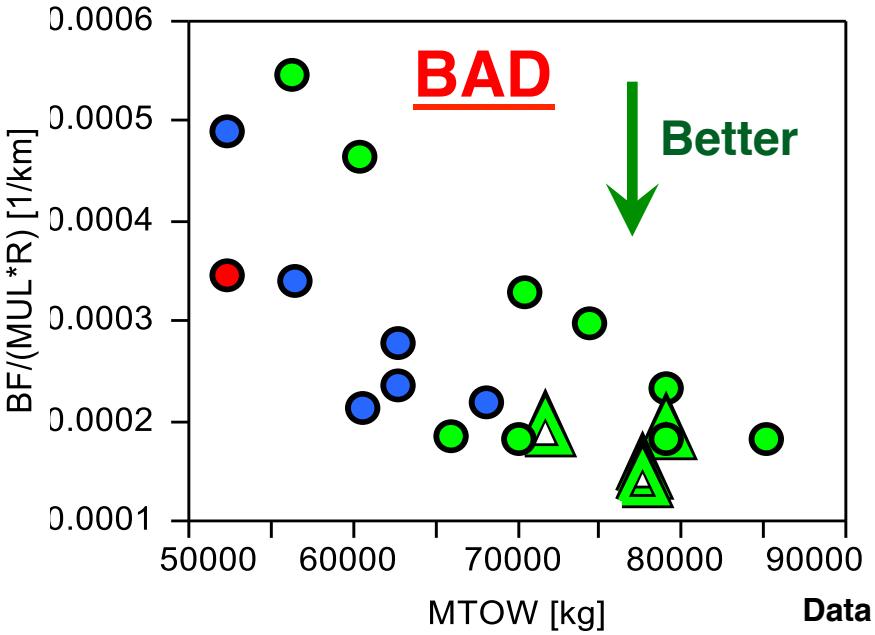
Single-Aisle Aircraft Class Only
MUL = Maximum useful load
P60 = evaluation option at 60% maximum payload

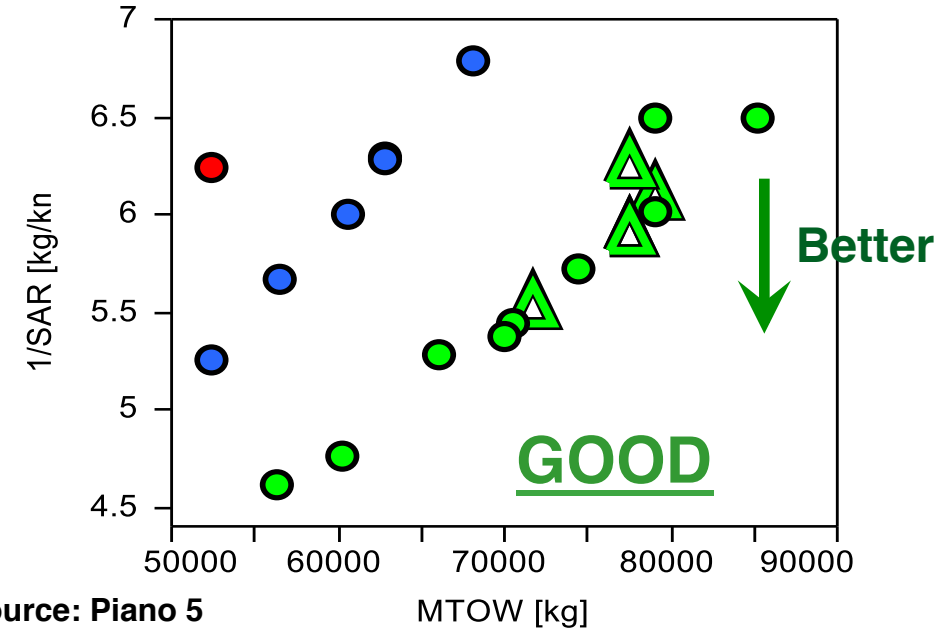
Differentiate Technology Levels

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2003-2013

1/SAR shows clear trend with advancing aircraft generations

Single Aisle Aircraft Family





Data Source: Piano 5

BF/(MUL*R):
Evaluated at maximum range with 60% of Max. Structural Payload (P60) , where MUL is maximum useful load

Legend

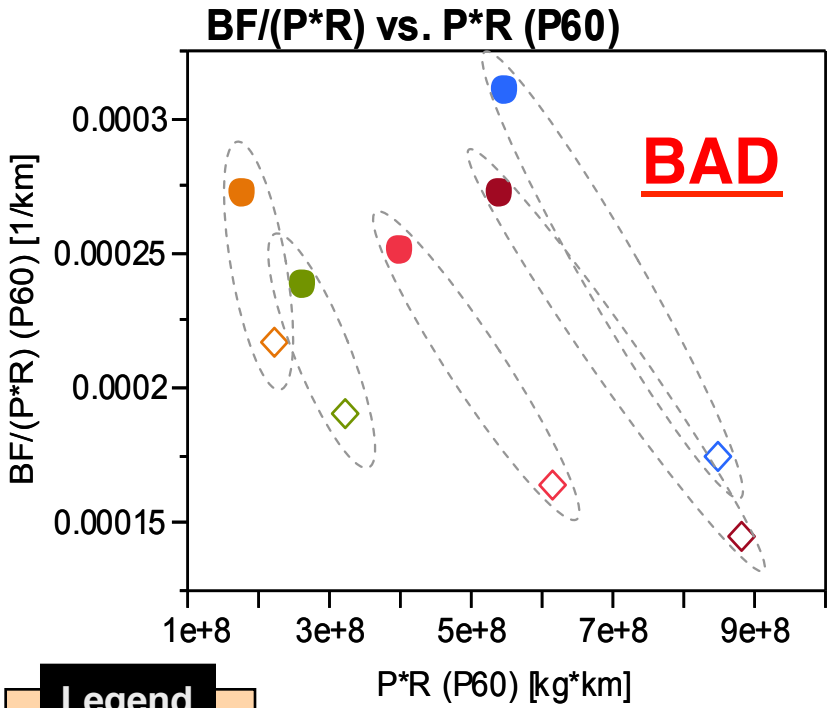
Aircraft Type	*Certification Date*
● Passenger	Red: 1960's
△ Business Jet	Blue: 1980's
◇ Freighter	Green: 1990's-2000's

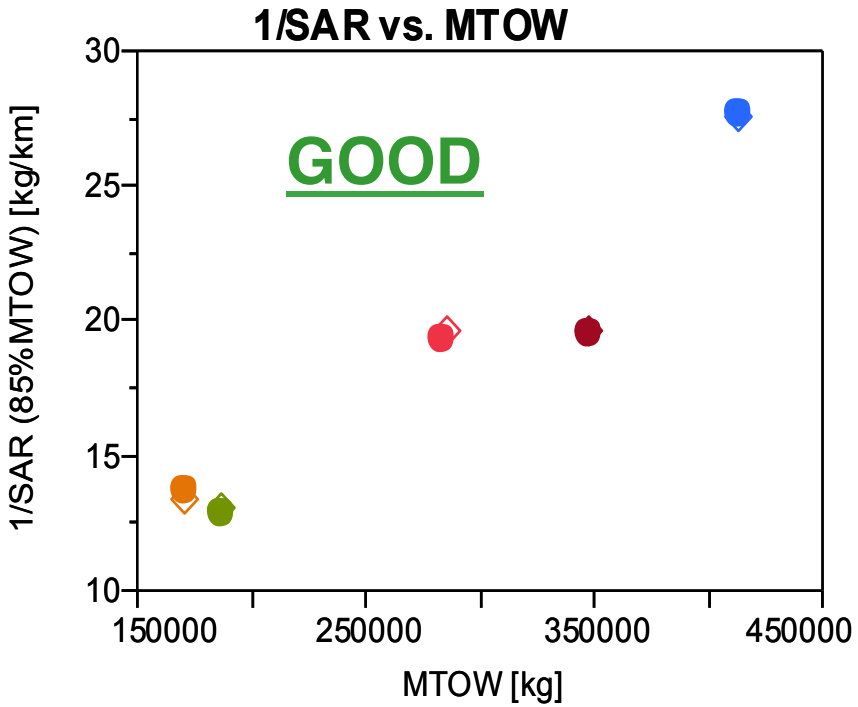
1/SAR:
Evaluated at 85% of MTOW (optimum speed and altitude)

Independent of Purpose

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10 YEARS
2003-2013

- Investigate performance of five comparable pairs of Passenger/Freighter aircraft variants
- 1/SAR vs. MTOW does not discriminate based on aircraft configuration





Legend

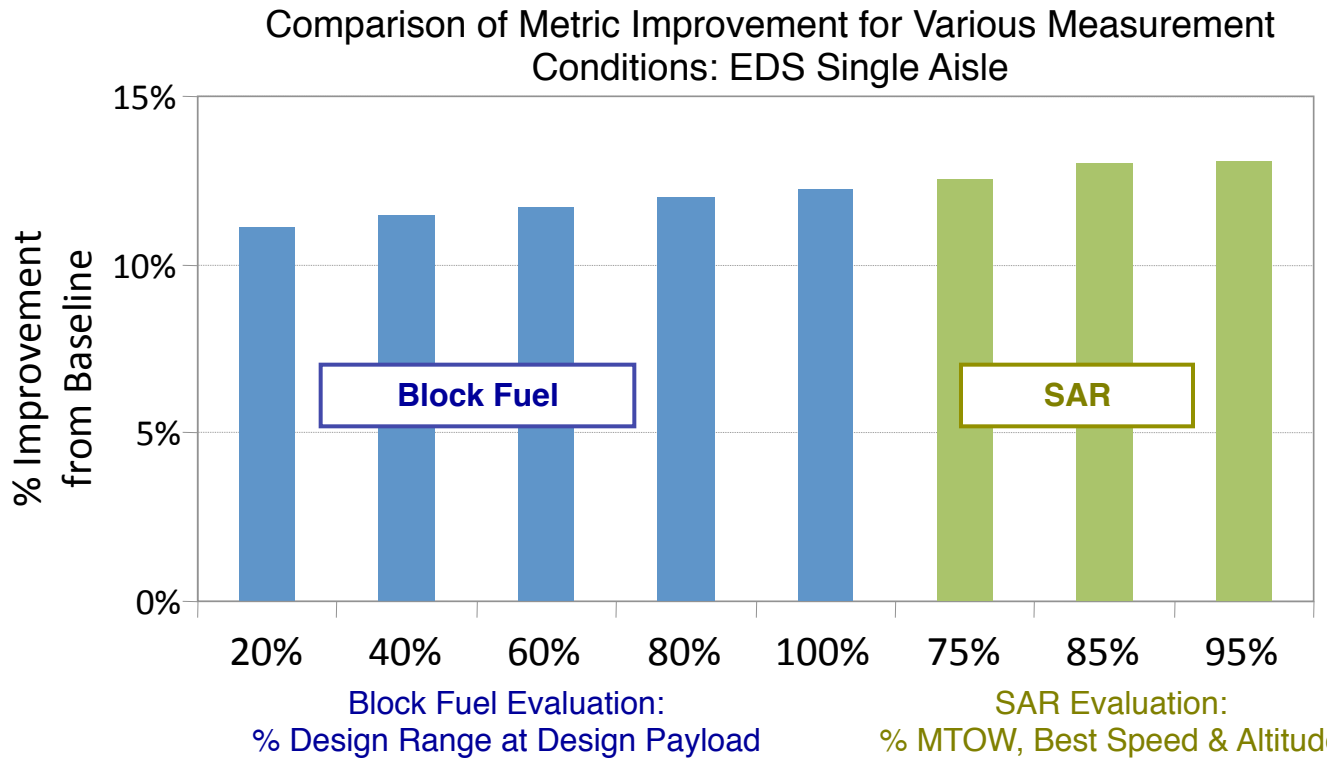
- Passenger
- Freighter

Variants of the same aircraft are shown in the same color

Correlation between Improvements in Metrics vs. Fuel Burn in Day-to-Day Operations

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2003-2013

- Block fuel and 1/SAR metric performance compared for 10% fuel flow reduction
- Positive correlation between block fuel, 1/SAR across missions

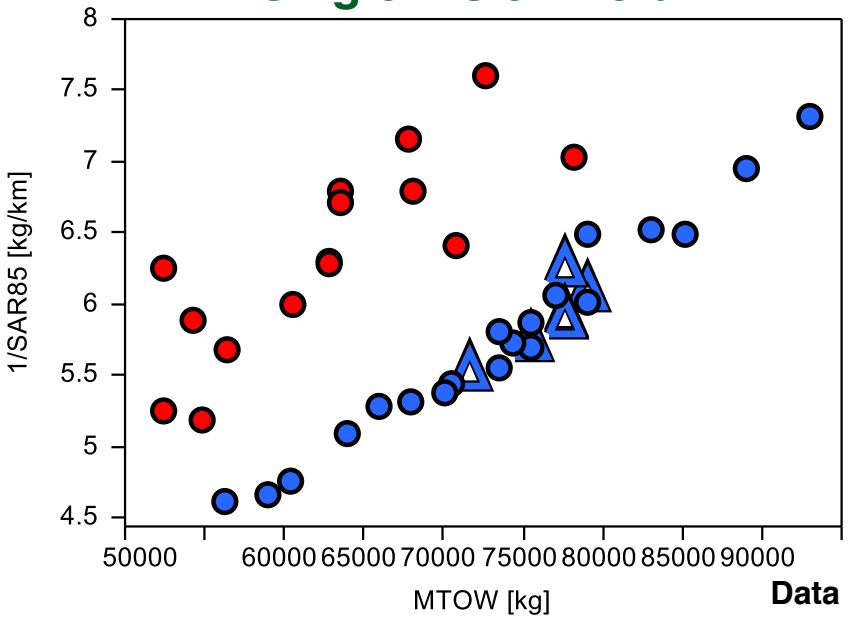


Fairness Across Stakeholders

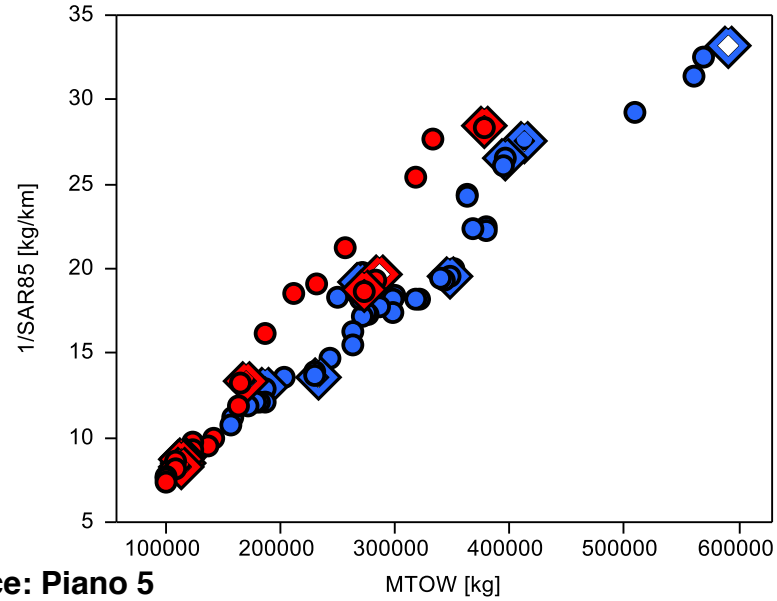
PARTNER
10 YEARS
2003-2013

- The 1/SAR vs. MTOW metric-CP pair does not differentiate aircraft based the type or category

Single Aisle Aircraft



Large Aircraft



Data Source: Piano 5

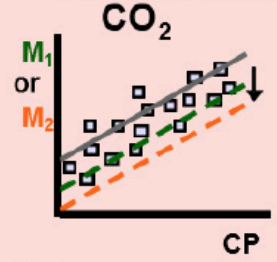
Legend

Aircraft Type	*Production Status*
Passenger	Blue-In production
Business Jet	Red-Out of production
Freighter	

Approach for Assessing Effectiveness in Reducing CO_2 Emissions

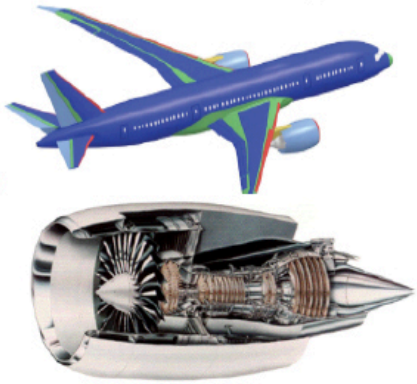
PARTNER
10 YEARS
2003-2013

Standards



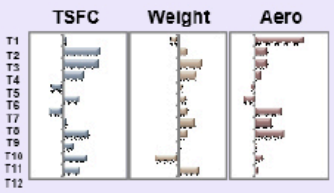
- Metric
- Correlation Parameter
- Evaluation Option
- Notional Limit Line
- Applicability
- Implementation Date

EDS
Vehicle Design

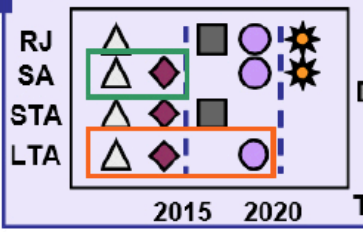


Technologies

- Benefit
- Cost
- Applicability
- Availability



Technology Roadmaps



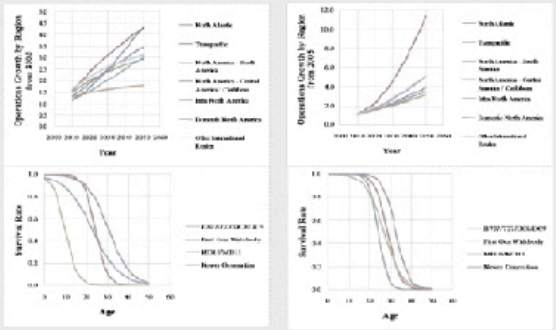
Scenarios

Scenario 1
Scenario 2

...

Operations

Demand Forecast
Aircraft Retirements
Replacements Schedule



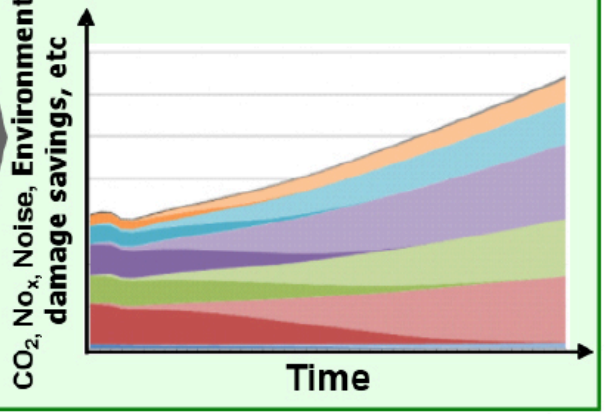
Vehicle Performance Characteristics

GREAT/AEDT
Fleet Analysis



- FB/Operation
- Total Ops
- Total FB

Fleet Environmental and Cost Impact
(AEDT, APMT-I)

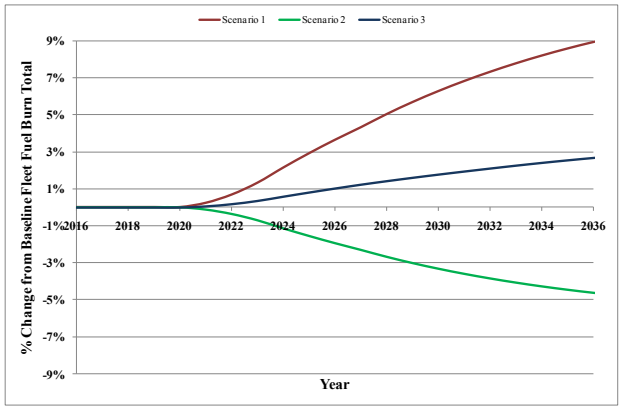


Example System-Wide Results

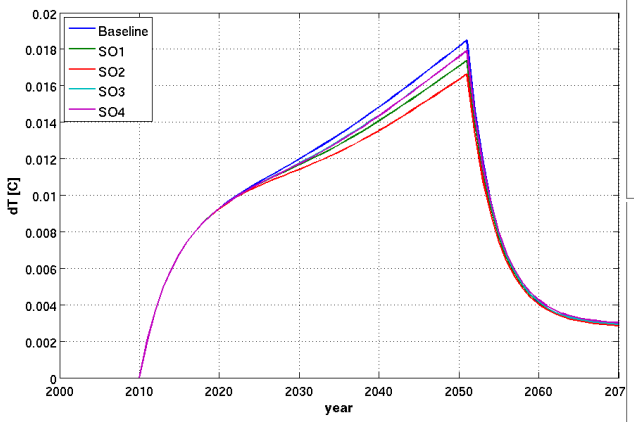
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10 YEARS
2003-2013

- Developed an approach utilizing many of the capabilities in the FAA Tool Suite to assess various scenarios of different metric systems
- Example approach considered the system wide implications of various metric systems, including:
  - Developed sample metric system scenarios with technology roadmaps and packages for notional technology responses
  - Characterized impact of scenarios by determining domestic aviation CO_2 emissions with time
  - Characterized the influence of scenarios on global NO_x emissions and noise

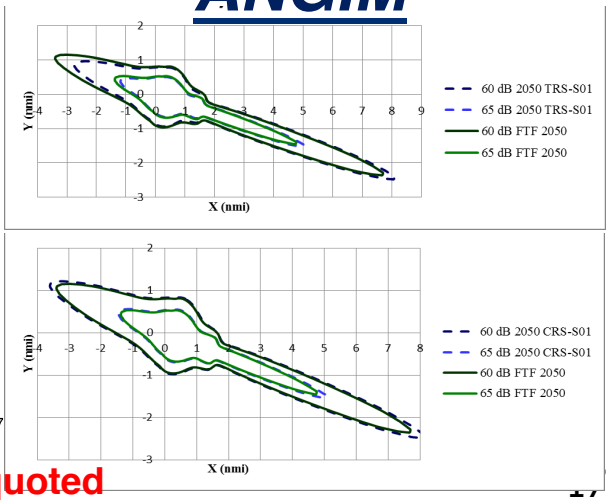
EDS and GREAT



APMT-I



ANGIM



Illustrative results. Not to be cited or quoted

Key Outcomes

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10 YEARS
2003-2013

- Project 30 team recommended 1/SAR vs. MTOW as a promising metric system to serve as the foundation for the CO_2 certification standard framework

- WG3 members accepted this system as promising but had additional concerns

- Further research was conducted to address CAEP stakeholder concerns and resulted in the addition of an augmentation parameter and multi-evaluation options

What difference did P30 make?

PARTNER
10 YEARS
2003-2013

- PARTNER Project 30 has supported CAEP9/WG3/CO2Task Group in assessing aircraft CO_2 certification metric systems for 4 years
- On 11 July, 2012, CAEP Steering Group "reached unanimous agreement on a CO_2 metric system to underpin the CO_2 standard"[1]
- Project 30 work contributed to CAEP decision by showing that the CO_2 metric system will meet the ECs
- Project 30 extensively exercised many of the capabilities within the FAA Tool Suite including EDS, GREAT, AEDT, and AMPT-I

"The analyses done by PARTNER have always been comprehensive, thorough, and full of insights, and it is obvious to everyone in the CAEP CO_2 Task group that the progress of ICAO aircraft CO_2 standard would have not been achieved without PARTNER's help."

- Hikaru Takami (Mitsubishi Heavy Industries, Ltd.)

1 Source: http://www.icao.int/environmental-protection/Documents/CO2%20Metric%20System%20-%20Information%20Sheet.pdf

Interfaces and Communications

PARTNER
10 YEARS
2003-2013

- Collaborated with numerous research projects being sponsored by NASA (e.g., ERA, FW, Boeing's SUGAR team), FAA (CLEEN), and industry at GT and MIT to provide additional technology and aircraft and/or engine configuration data for N+1 to N+3 time frame
- Multiple publications available on PARTNER website
- External
  - Extensive interaction with CAEP:
    - Numerous working and information papers for all of the CAEP/9 cycle meetings and workshops
    - Weekly, sometimes daily, teleconferences
    - Submissions and presentations to CO2TG subgroup teleconferences
- Within PARTNER
  - Collaboration with other PARTNER projects including P14, P31, P36, and P43
  - Numerous members of the advisory board

Summary

PARTNER
10 YEARS
2003-2013

- Supported the domestic and international decision making process that is developing an aircraft CO_2 certification requirement
- Leveraged other PARTNER projects to inform the FAA
- **First time that the linkage between the FAA's Tools Suite (EDS→GREAT/ANGIM→AEDT→APMT-I) is being executed**
- The P30 team has been a crucial player in providing sound technical insight to AEE and the international community on a complex problem
- The team will continue to support further analysis on the CAEP selected metric system

Contributors over the Years

PARTNER
10 YEARS
2003-2013

- **Georgia Tech**: Prof. Dimitri Mavris, Dr. Michelle Kirby, Dr. Taewoo Nam, Dr. Dongwook Lim, Dr. Holger Pfaender, Dr. Elena Garcia, Chris Perullo, Graham Burdette, Bryan Boling, Samuel Borenstein, William Whittecar, Omar Valverde, Robert Taylor, Robert Willett, J. Scott Wilson, Steven Isley, Sheldon Smith, Thomas Carroll, Clark Kjorlaug
  - Special thanks to the Project 14, 36, and 43 teams and the NASA ERA and FW teams at GT
- **MIT**: Brian Yutko, Prof. R. John Hansman, Dr. Alex Mozdzanowska, Prof. Ian A. Waitz
- **Booz Allen Hamilton**: Dr. Philippe A. Bonnefoy, Alice Fan
- **FAA:** Curtis Holsclaw, Ralph Iovinelli, Mary Alice Locke, Dr. Lourdes Maurice, Laszlo Windhoffer

PARTNER RESEARCH, 2003 – 2013

PUBLIC SYMPOSIUM

OPERATIONS

Overview

Session Chair: Odilyn Luck

Presentation by: Prof. John Hansman, MIT

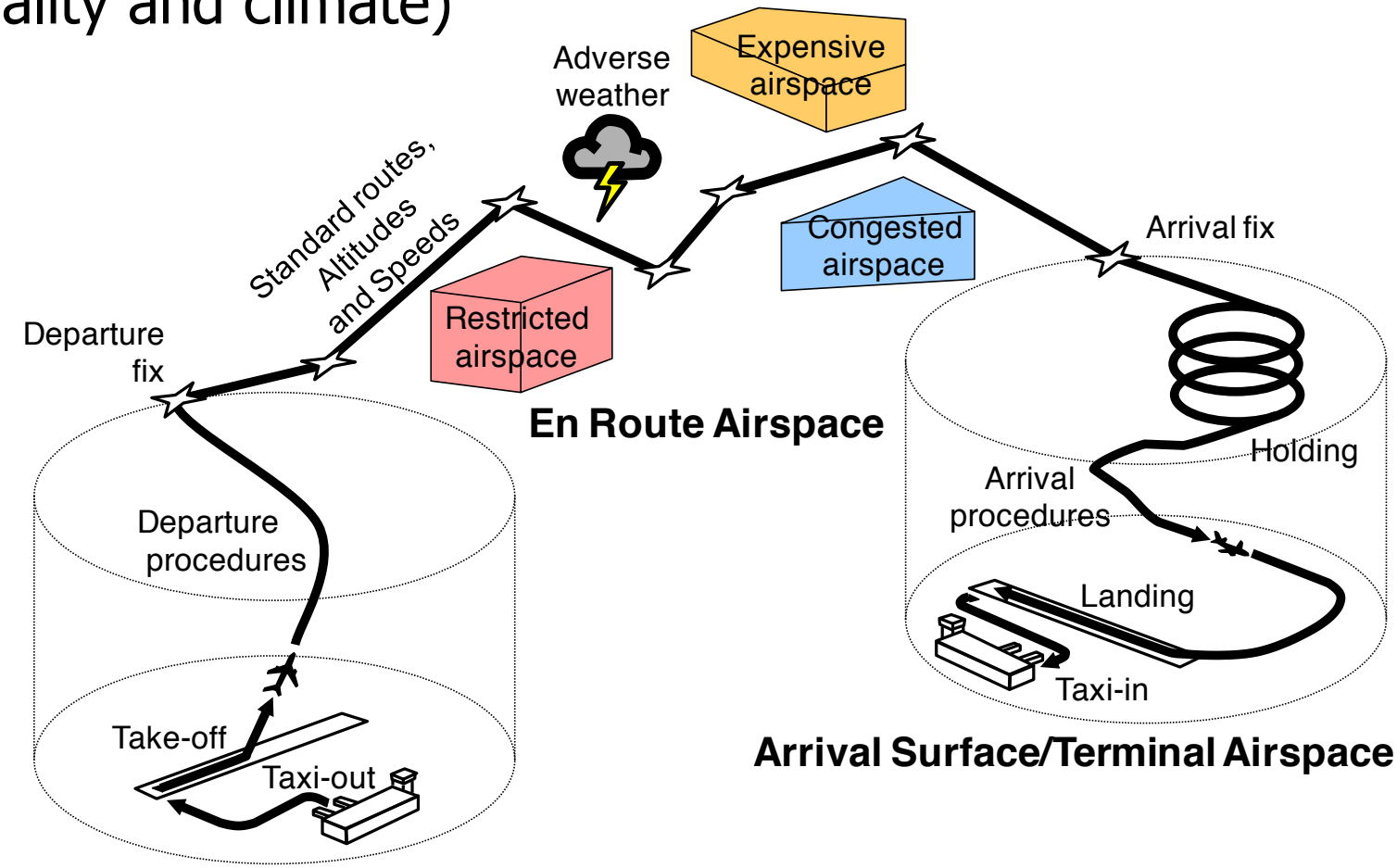
Opinions, findings, conclusions and recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of PARTNER sponsor organizations.

10th Year Public Symposium
March 1, 2013
Costa Mesa, CA

PARTNER
Partnership for Air Transportation Noise and Emissions Reduction

Motivation

- Improving aircraft operations is one of the most rapid actions that can reduce environmental impacts (noise, air quality and climate)



Challenges

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10 YEARS
2003-2013

- Many constraints to consider

Safety

Environment

Capacity

Economics

Policy/Regs

Aircraft Performance

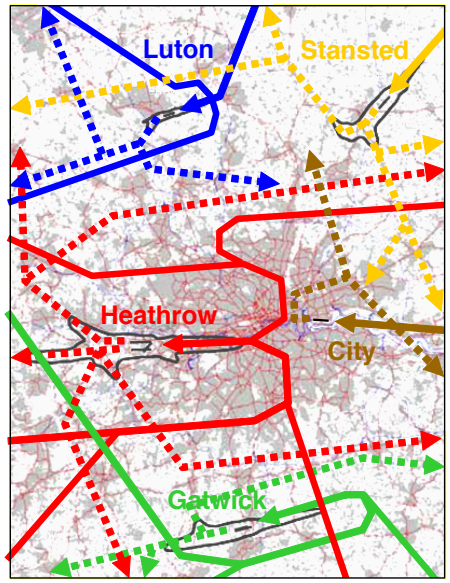
Air Traffic Control







Airline Operating Practices



Research

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2003-2013

- Prior aircraft operations research often focused on "targets of opportunity"

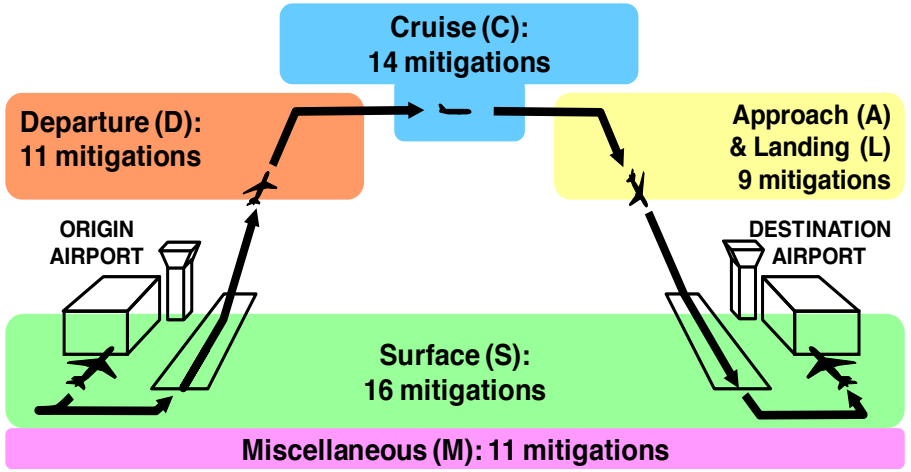
- PARTNER operations research portfolio designed to systematically:
  - ***Identify*** range of opportunities for improved operations to reduce environment impact
  - ***Analyze*** specific operational improvements with most promise to assess benefits potential
  - ***Implement*** prototype improvements to test validity in operational setting

- Example PARTNER programs highlight these steps

Research: Project 32
Near-Term Operations Improvements

PARTNER
10 YEARS
2003-2013

- Objective: Identify/evaluate operational techniques to reduce fuel burn and environmental impacts of aviation in the near/mid-term with minimal implementation barriers
- Approach:
  - Identification (stakeholder interviews, literature reviews, etc.)
  - Systematic evaluation against environment, system metrics
  - Prioritization of areas for greater focus
- Outcomes:
  - Identification, evaluation and prioritization of 75 options
  - Detailed analysis of benefits & barriers of promising options
    - Cruise Altitude and Speed Optimization
    - Delayed Deceleration Approaches
  - Promote deployment of best practice operations



Operational Mitigation to Reduce Environmental Impact: Partial List of Selected Mitigations

PARTNER
10 YEARS
2003-2013

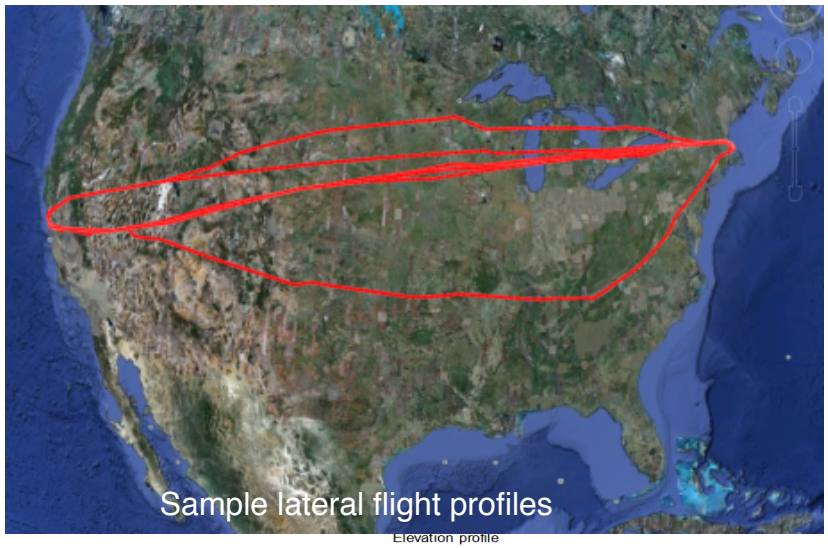
Mitigation	Fuel (F)	Climate (C)	Air Quality	Noise	Implementability	Potential Impact
SURFACE (S)						
S-1: Queue Management Systems						
S-1.2: Advanced Systems (optimized strategies)	**S**	**S**	**P**	**S**	**Medium**	**Strong**
S-2: Taxi Fuel Minimization						
S-2.4: Improved surface situational awareness, harvesting ASDE-X data	**S**	**S**	**P**	**S**	**Easy**	**Mod**
S-5: Improved coordination tools						
S-5.1: Improved information sharing	**S**	**S**	**S**	**S**	**Medium**	**Strong**
S-5.2: Flight plan change delivery over datalink	**S**	**S**	**S**	**S**	**Medium**	**Mod**
DEPARTURE (D)						
D-1: Departure procedures						
D-1.10: Operating in best noise configuration	**0/A**	**0/A**	**0/A**	**P**	**Easy**	**Strong**
D-2: Increased flexibility in departure routes						
D-2.1: RNP/RNAV Enabled SIDs	**S**	**S**	**P**	**S**	**Medium**	**Mod**
CRUISE (C)						
C-1: Horizontal Route Efficiency						
C-1.1: RHSM, multi-laning	**P**	**P**	**0**	**0**	**Hard**	**Strong**
C-1.2: Minimize lateral route inefficiency	**P**	**P**	**0**	**0**	**Med**	**Strong**
C-2: Vertical Routing Efficiency						
C-2.2: Increased directional airways	**P**	**P**	**0**	**0**	**Easy**	**Mod**
C-2.3: Cruise climb	**P**	**P**	**0**	**0**	**Med**	**Strong**
C-2.4: Step-climb	**P**	**P**	**0**	**0**	**Easy**	**Mod**
C-2.5: Increase priority for giving requested/optimal altitudes	**P**	**P**	**0**	**0**	**Easy**	**Mod**
C-3: Speed Efficiency						
C-3.1: Individual aircraft fuel-optimized cruise speeds	**P**	**P**	**0**	**0**	**Hard**	**Strong**
C-3.2: Cruise Mach reductions	**P**	**P**	**0**	**0**	**Easy**	**Strong**
C-3.3: More efficient passing options	**P**	**P**	**0**	**0**	**Med**	**Strong**

6

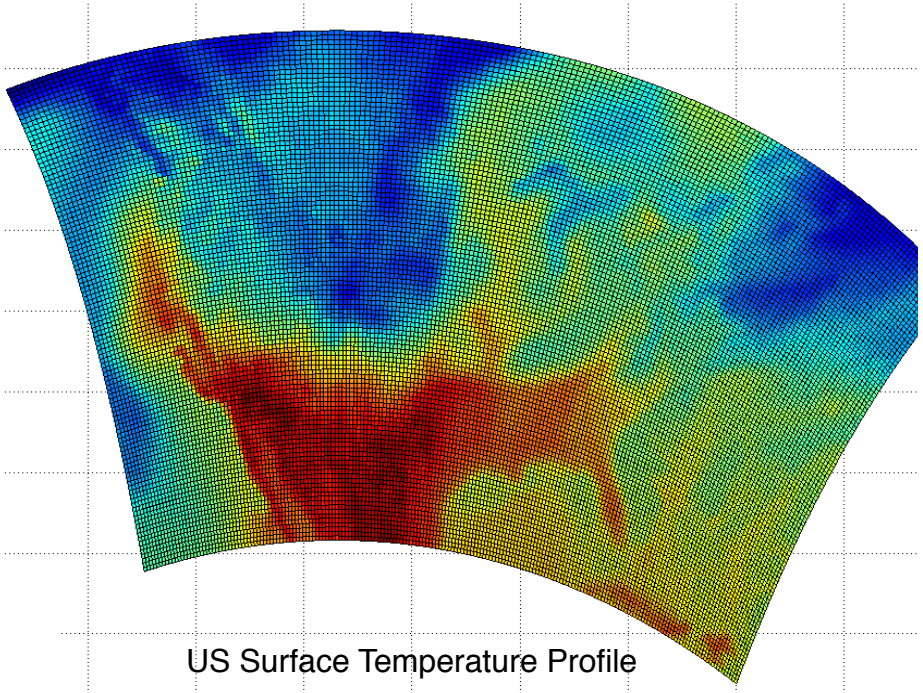
Speed and Altitude Analysis: Data Sources

PARTNER
10 YEARS
2003-2013

- **ETMS Flight Data**
  - All domestic flights, 9/21/2009
  - Trajectory data in 1 min steps
    - Altitude
    - Latitude/Longitude
    - Groundspeed
  - Filed flight plan information



- **NOAA Atmospheric Data**
  - Temperature
  - Wind components
  - Vertically spaced at 30 different pressure levels
  - Laterally spaced at 32-by-32 km gridpoints

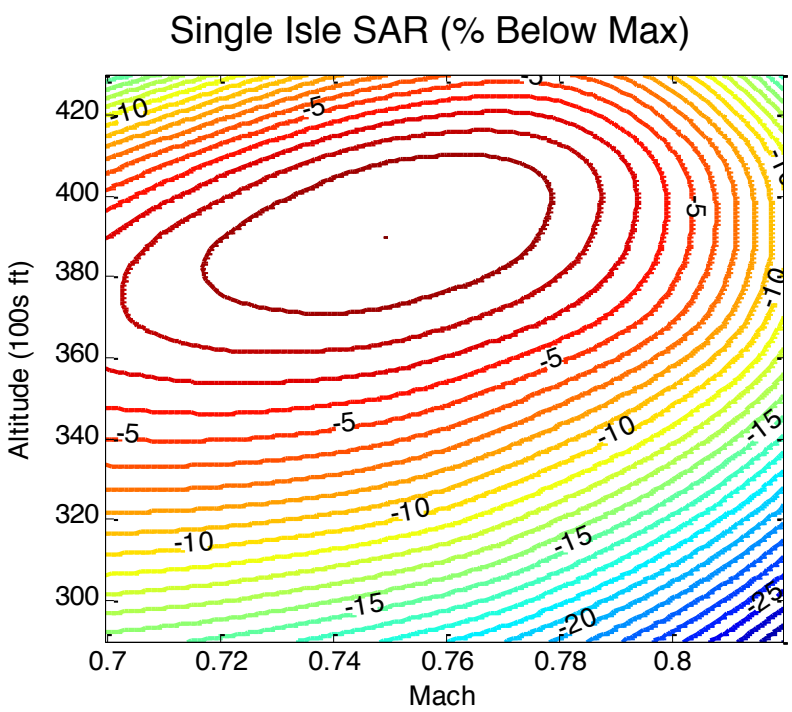


US Surface Temperature Profile

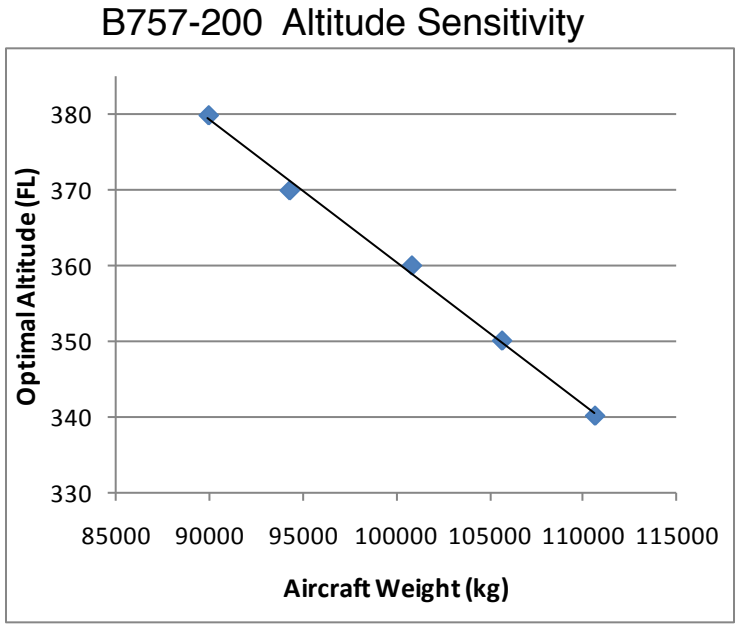
Piano-X Aircraft Performance

PARTNER
10 YEARS
2003-2013

- Primary focus on Standard Air Range (SAR): distance flown per kg of fuel
- SAR table of speed vs altitude mapped for each aircraft at one weight
- Fundamental correlation applied to include SAR sensitivity to weight



- Utilized step climb profiles in Piano-X to match optimum altitude with weight
  - Validated results by checking that weight changed approximately proportionally with air density



Potential Efficiency From Optimal Speed and Altitude

PARTNER
10 YEARS
2003-2013

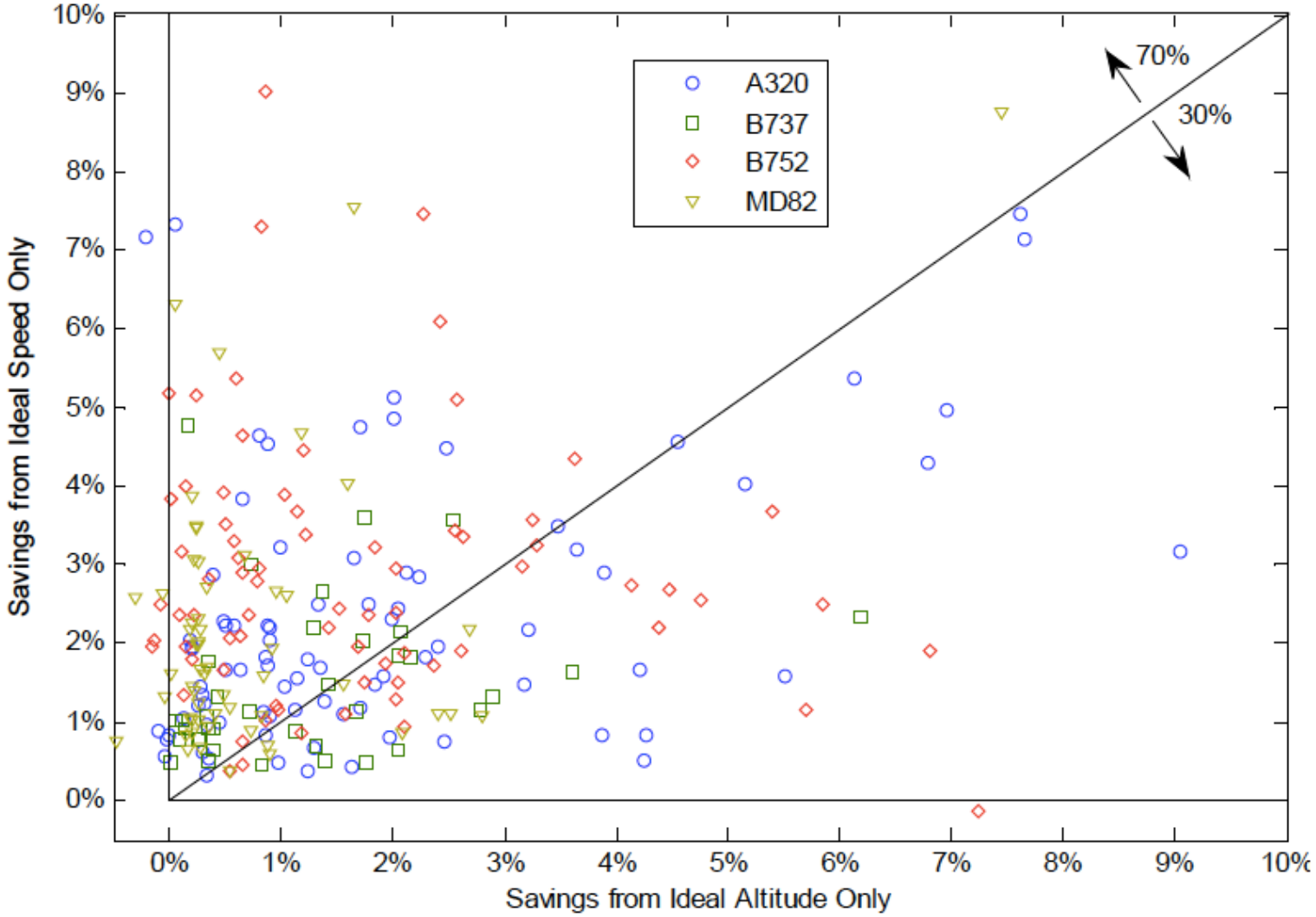
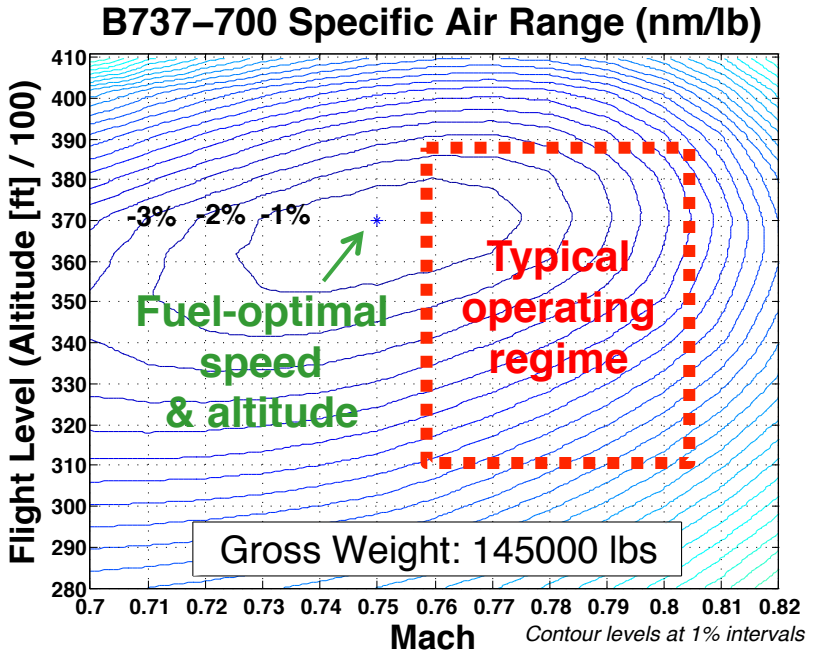


Figure 26. Optimum speed-only versus optimum altitude-only fuel burn reduction potential for all flights, categorized by aircraft type.

Research: Project 32
Cruise Altitude & Speed Optimization (CASO)

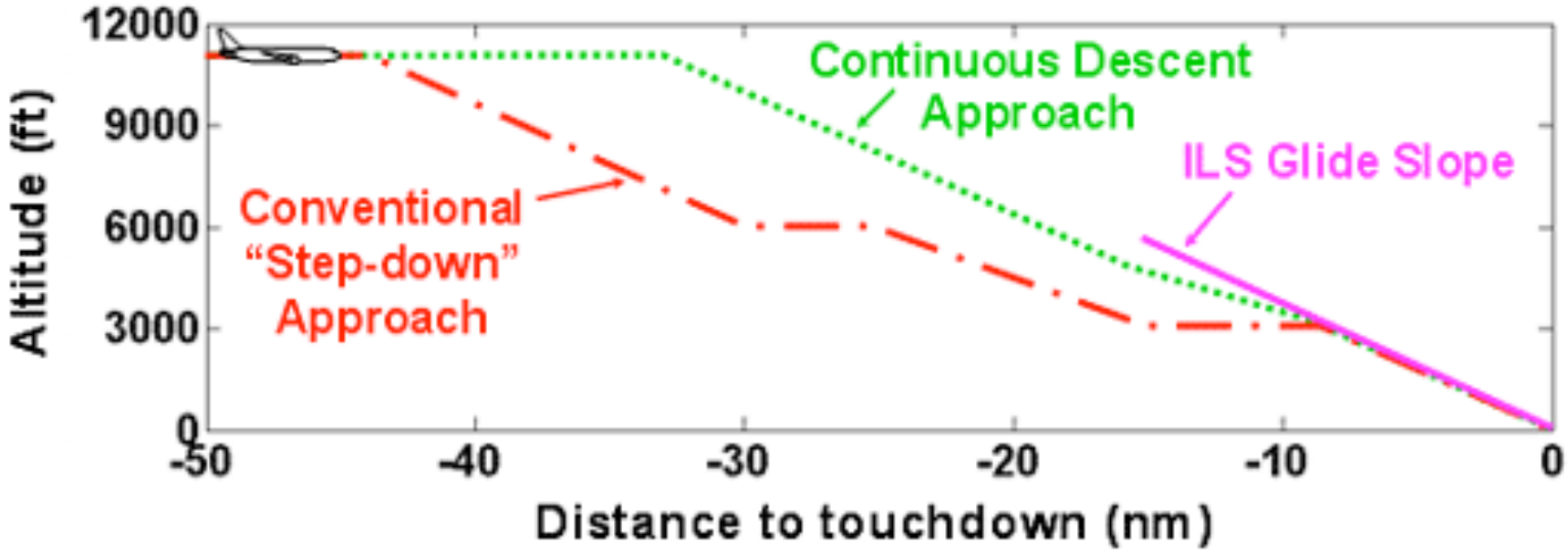
PARTNER
10 YEARS
2003-2013

- Aircraft often fly off their min fuel speed (maintain schedule/ATC) and optimal altitude (ATC procedures)
- Approach
  - Identifying cruise altitude/ speed inefficiencies in current operations
  - Estimate fuel/emissions benefits from CASO
  - Stakeholder collaboration to refine/implement options
- On-going research suggests up to 5% fuel & emissions saving potential



Speed Profile	Optimal	Optimal	Unaltered
Altitude Profile	Optimal	Unaltered	Optimal
Cruise Benefit Potential	3.48%	2.40%	1.50%
Total Benefit Potential	2.63%	1.82%	1.15%
Fuel Reduction Potential (million gallons per year)	298.4	206.0	130.2
CO_2 Reduction Potential (million tons per year)	3.22	2.23	1.41

Research: Project 4
Continuous Descent Approaches

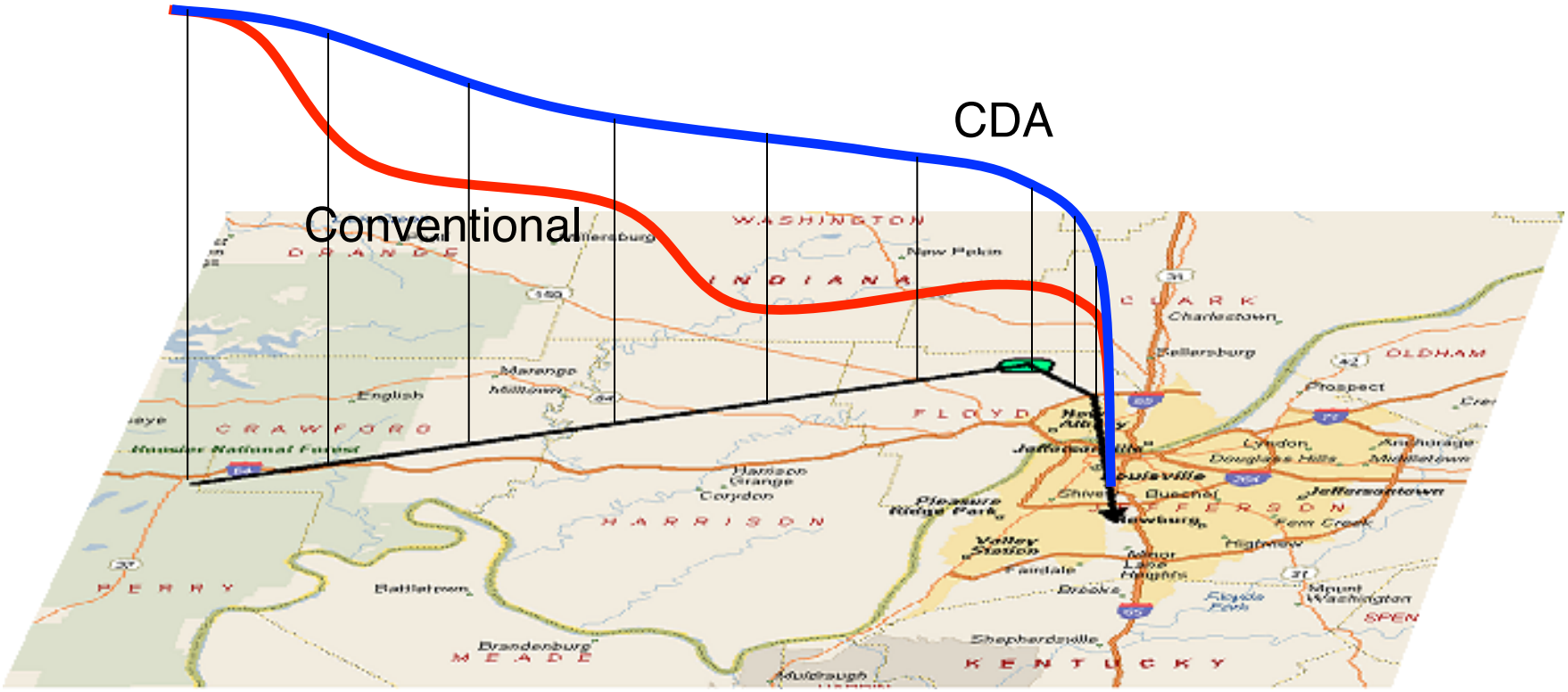


- Environmental Benefits
  - Higher trajectory and reduced thrust over much of the arrival and approach results in reduced noise impact
  - Less time spent below "mixing height" and reduced thrust results in reduced emissions
- Fuel Burn Benefits
  - Fuel and flight time savings due to less vectoring and less thrust at low altitude where jet engines are inefficient

Low Noise Approach Procedure Study at Louisville International (SDF)

PARTNER
10 YEARS
2003-2013

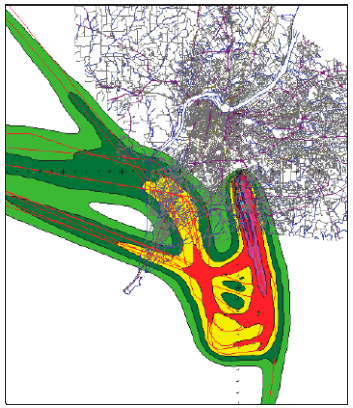
- Flight Demonstrations 2003 - 2004
  - MIT/NASA/Boeing/UPS/SDF with FAA
  - UPS B767 revenue flight night arrivals

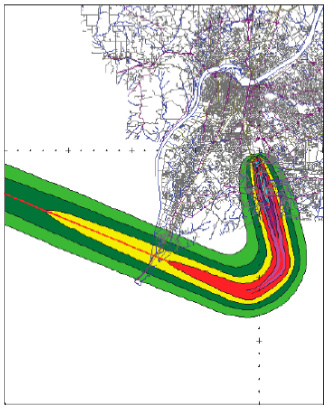


2004 SDF Flight Test

PARTNER
10 YEARS
2003-2013

- Significant environmental and economic benefits for CDA in real-world operations
  - Noise impact significantly reduced
    - Lower per aircraft noise levels (3 to 6 dBA; 7 to 15 NM from runway)
    - Impact concentrated in narrow corridors

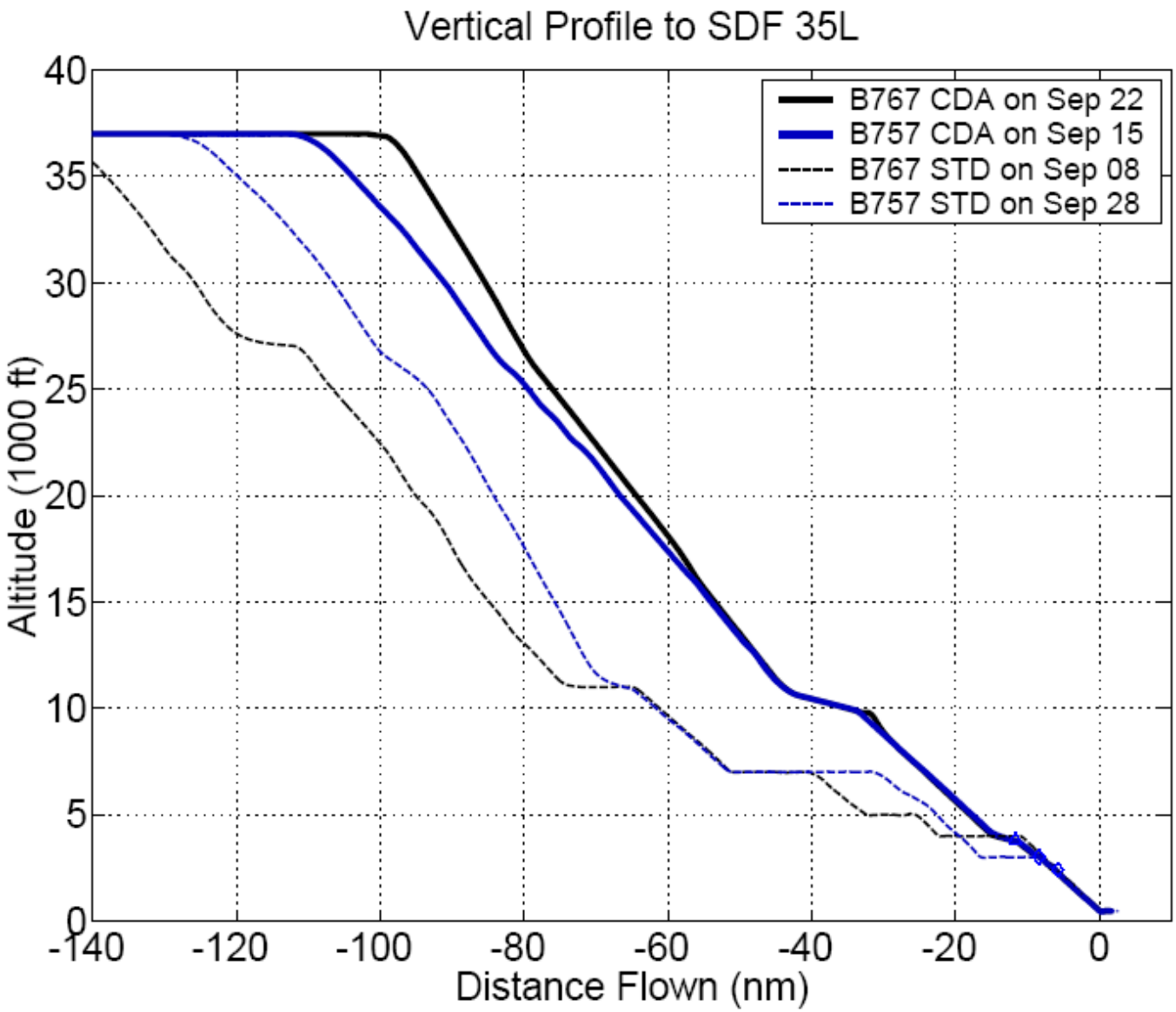




  - Local emissions significantly reduced
    - CO below 3,000 ft reduced by 12.7% (B-767) and 20.1% (B-757)
    - HC below 3,000 ft reduced by 11.0% (B-767) and 25.1% (B-757)
    - NOx below 3,000 ft reduced by 34.3% (B-767) and 34.4% (B-757)
  - Economic costs significantly reduced
    - Fuel to fly last 180 nm to runway reduced by 364 lbs/flight (B-767) and 118 lbs/flight (B-757)
    - Time to fly last 180 nm to runway reduced by 147 seconds/flight (B-767) and 118 seconds/flight (B-757)

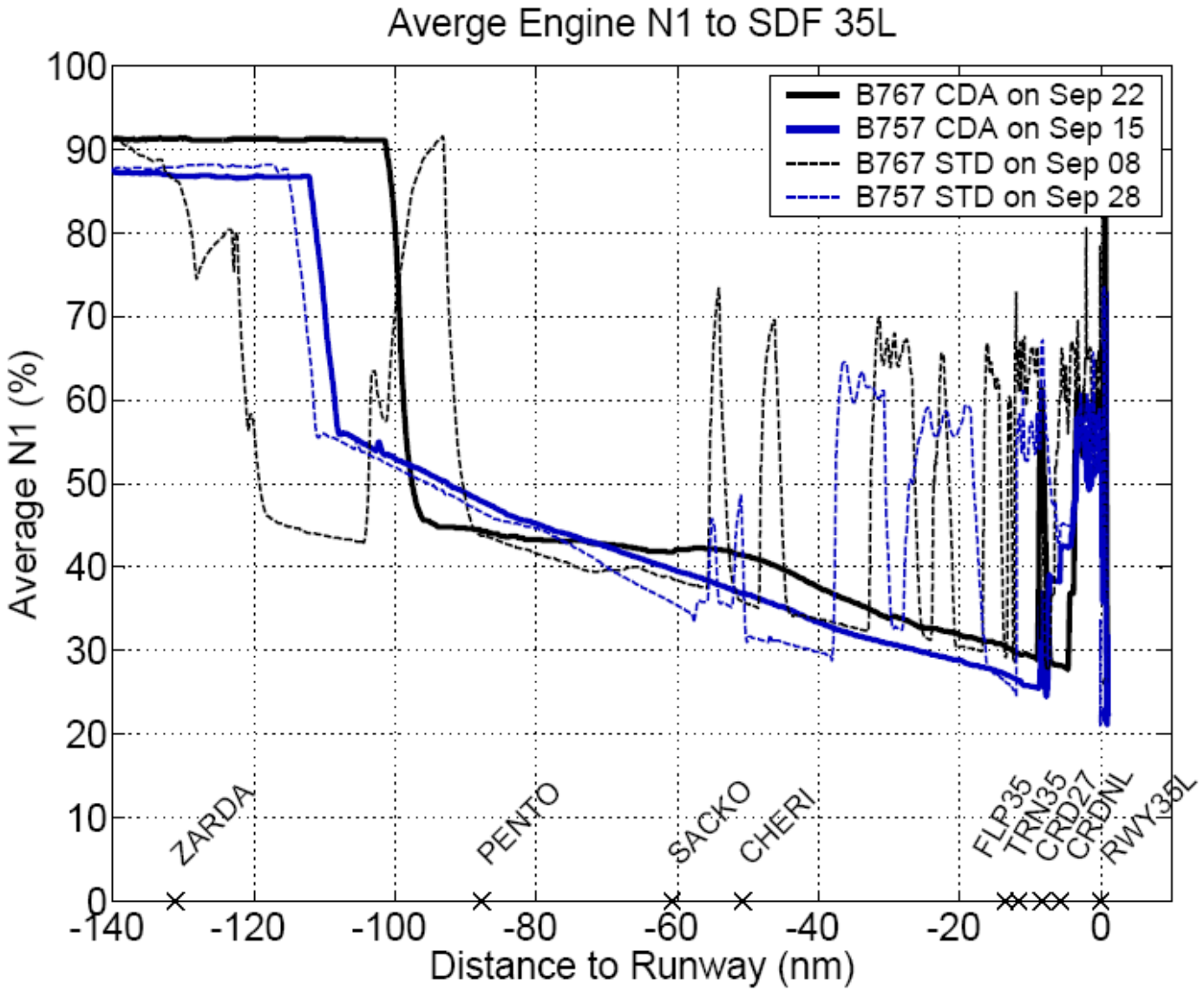
2004 SDF Flight Test

PARTNER
10 YEARS
2003-2013



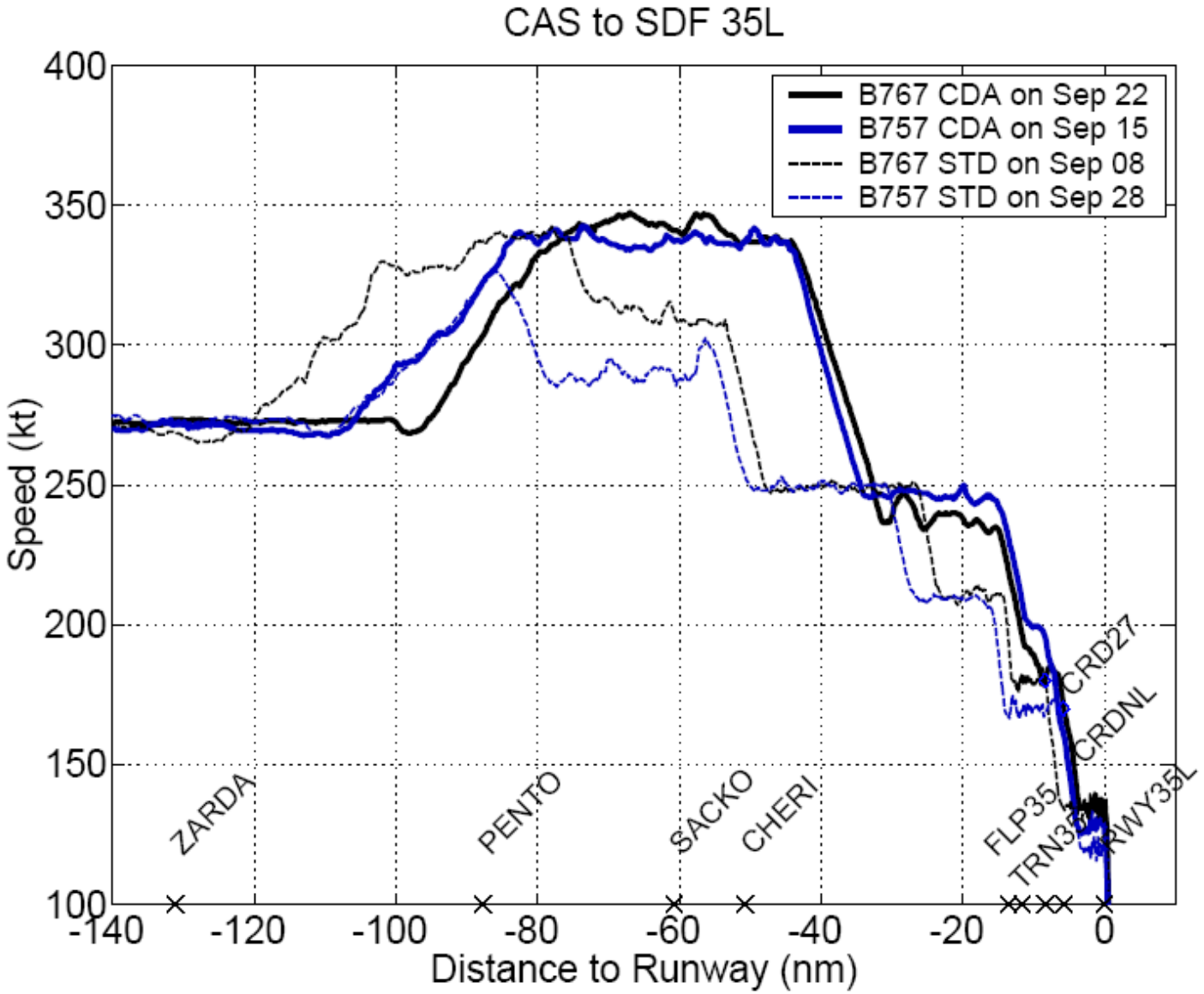
2004 SDF Flight Test

PARTNER
10 YEARS
2003-2013



2004 SDF Flight Test

PARTNER
10 YEARS
2003-2013

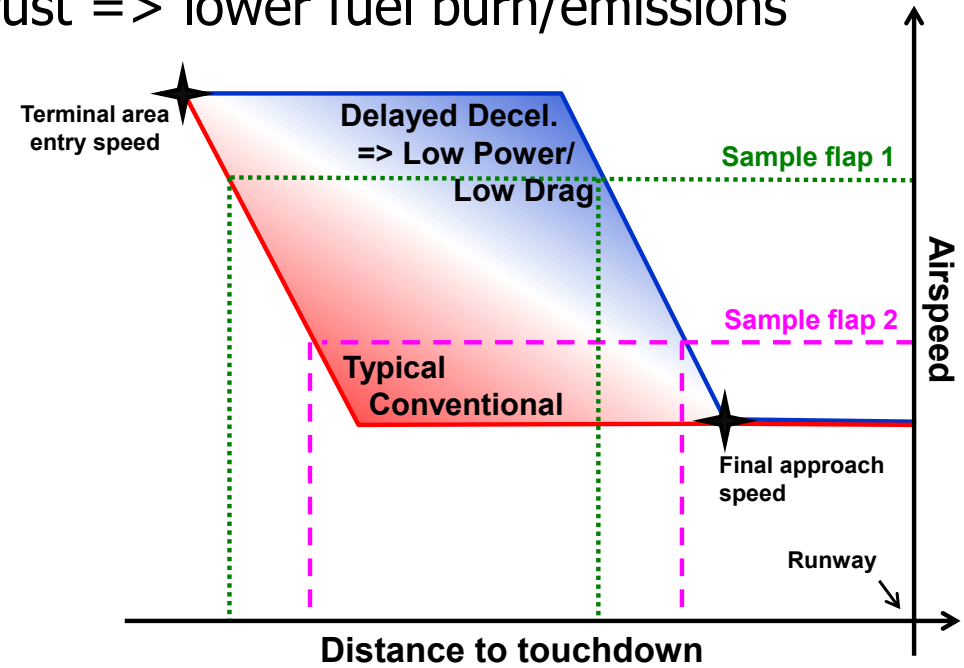


Research: Project 32 Delayed Deceleration Approaches (DDAs)

PARTNER
10 YEARS
2003-2013

- Aircraft maintain higher airspeed with clean aerodynamic configuration for as long as possible during approach
  - Lower drag => lower thrust => lower fuel burn/emissions

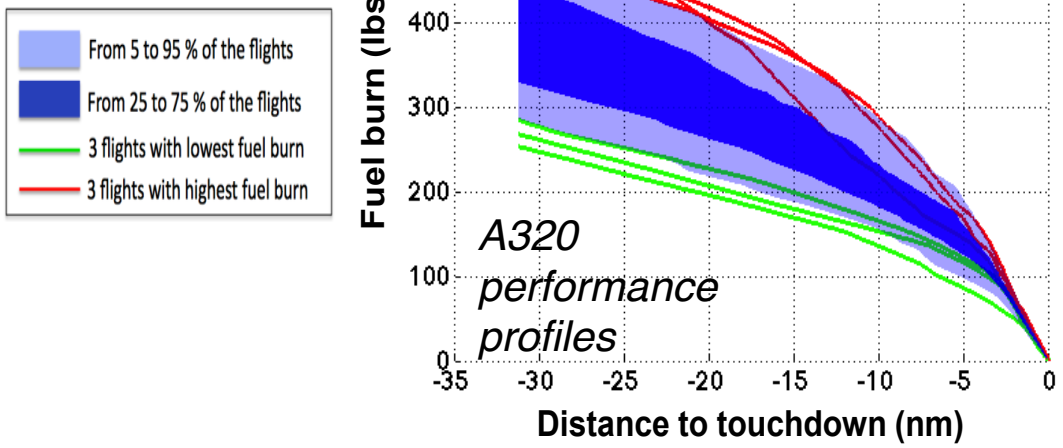


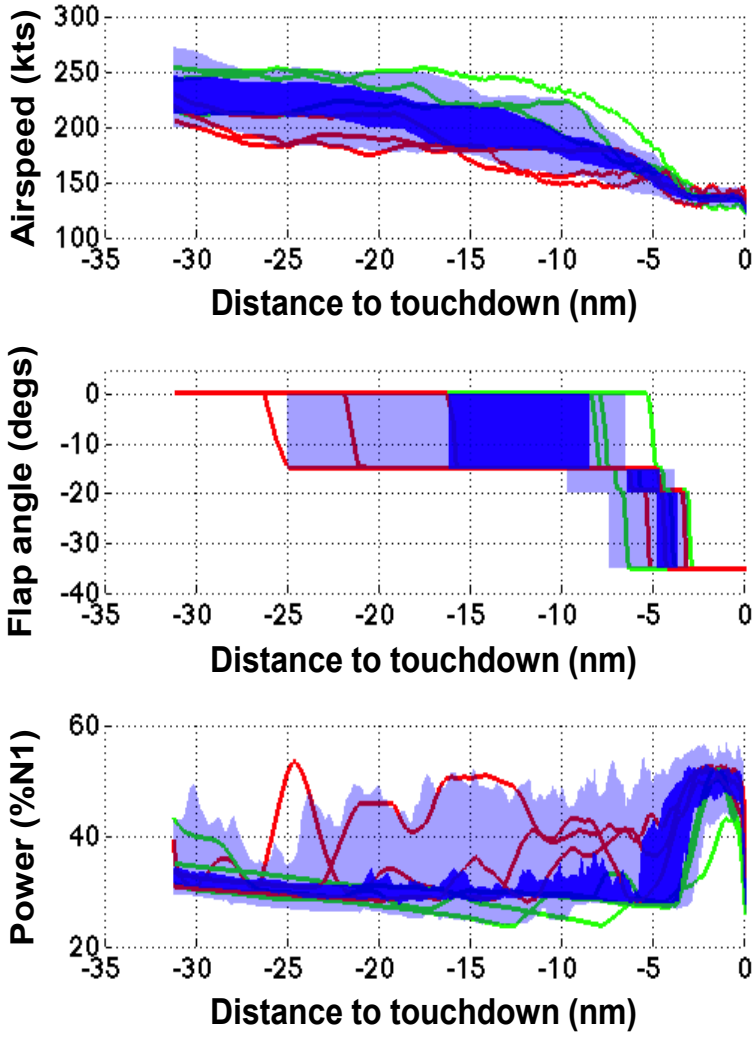


- Analysis shows 30-37% approach fuel saving potential
- On-going research identifying airports/times where DDAs may enable environment benefits to be achieved

Delayed Deceleration Approaches (DDAs)

PARTNER
10 YEARS
2003-2013

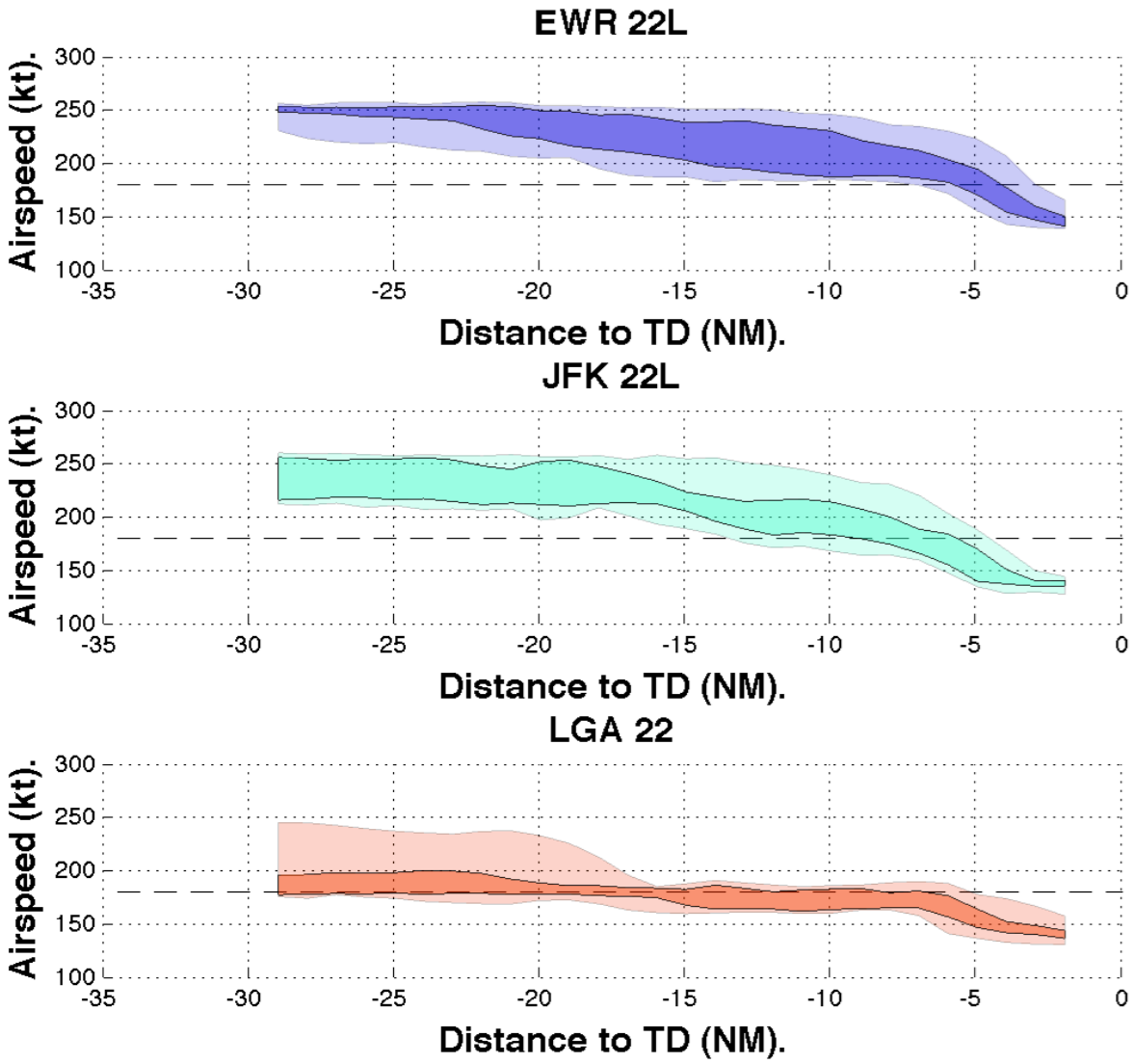




- Lowest fuel burn associated with DDAs
- Highest fuel burn had early deceleration and flap extension
- 30-37% average approach fuel savings suggested across 3 a/c types

Observed Deceleration Profiles

PARTNER
10 YEARS
2003-2013

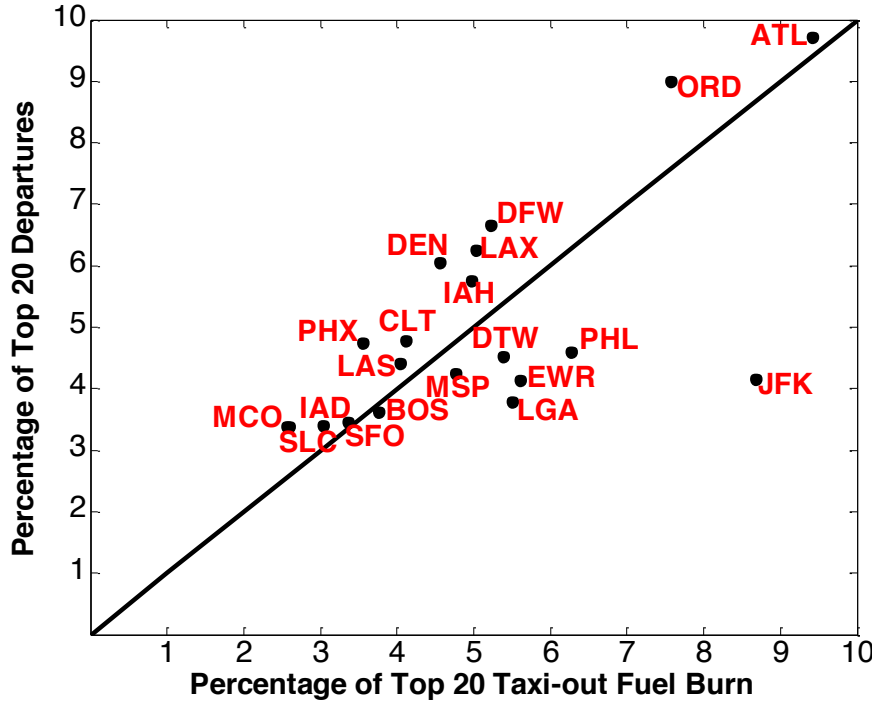


Earlier deceleration evident at LGA compared to EWR/JFK

Research: Project 21
Surface Congestion Management

PARTNER
10 YEARS
2003-2013

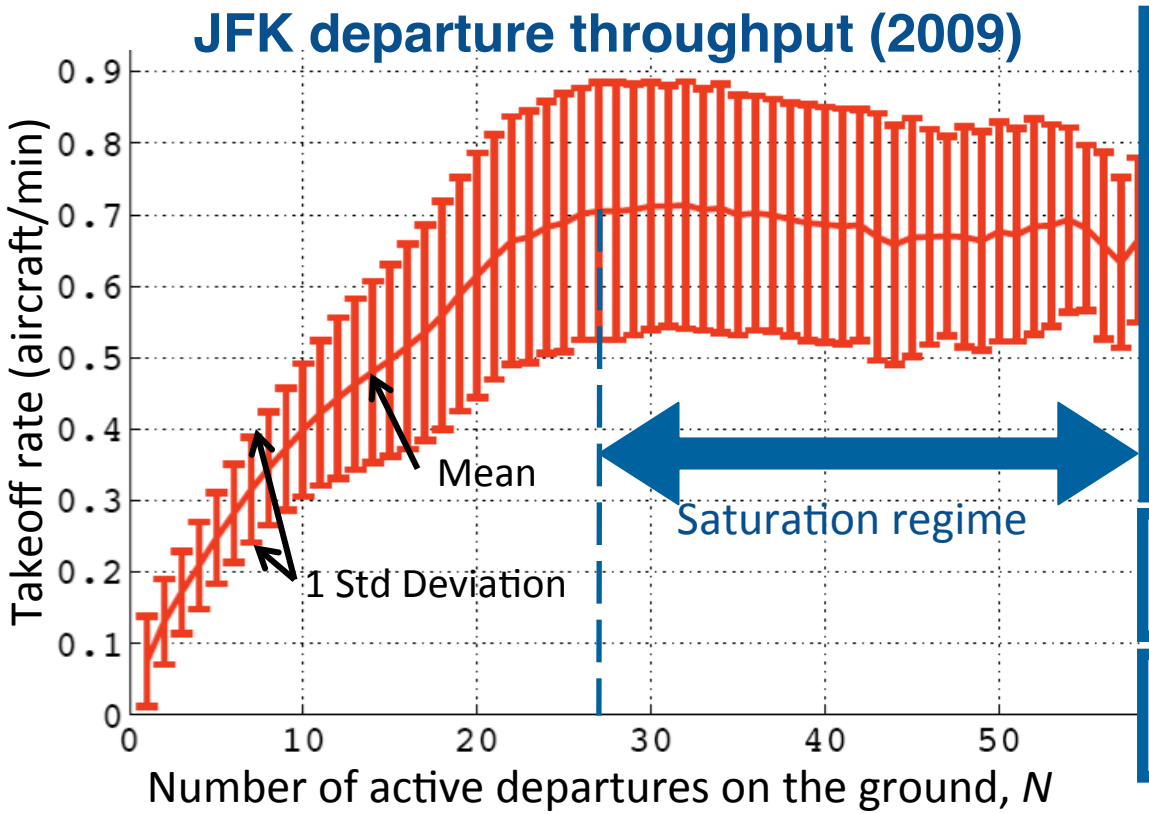
- Inefficiencies lead to increased taxi times, fuel burn, emissions
- Annually, at major airports in the US (2009 ASPM)
  - Over 32 million minutes taxi-out delay (over unimpeded times)
  - Over 13 million minutes taxi-in delay (over unimpeded times)
  - 19% of delays at OEP 35 airports due to terminal-area volume
- Taxiing aircraft contribute to surface emissions and noise



Problem: Airport Surface Congestion

PARTNER
10 YEARS
2003-2013

- Frequent congestion at major airports results in inefficient operations, and increased fuel burn and emissions



When JFK is saturated:

In Visual Meteorological Conditions, the average taxi-out time is **56 min**

In Instrument Met. Conditions, the average taxi-out time is **69 min**

Unimpeded taxi-out time: **16-19 min**

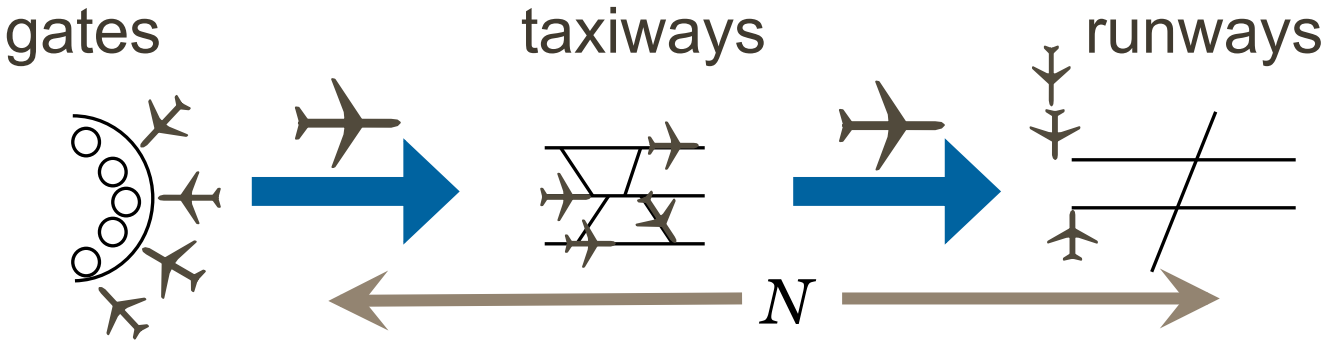
JFK is saturated 18% of the time in VMC, and 24% of the time in IMC

32% of departures at JFK takeoff during saturated periods

Simaiakis and Balakrishnan, *Transportation Research Record: Journal of the Transportation Research Board*, 2010
(Confirms Pujet, Delcaire and Feron, BOS 1999).

N Control - Pushback Rate Control

- Aircraft pushback from gates, start their engines, and then taxi until they takeoff



- Control pushbacks in order to maintain runway utilization while avoiding excessive levels of congestion
  - Minimal procedural modifications and change in ATC workload

N Control Demonstration
Boston Logan (2010-2011)

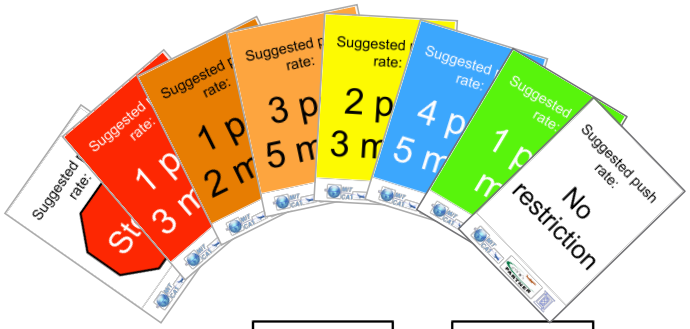
PARTNER
10 YEARS
2003-2013



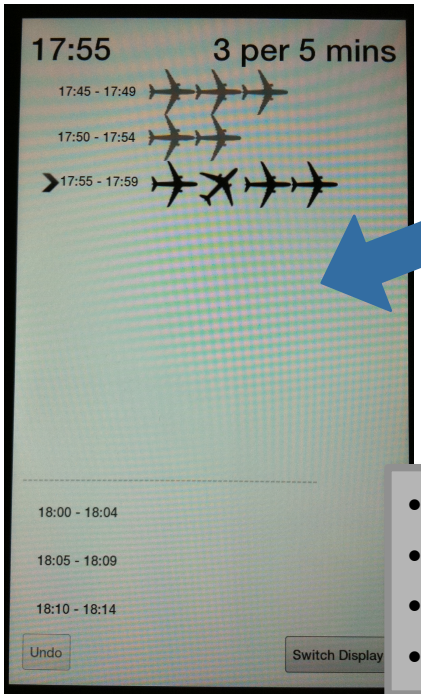
Interfacing with Air Traffic Controllers

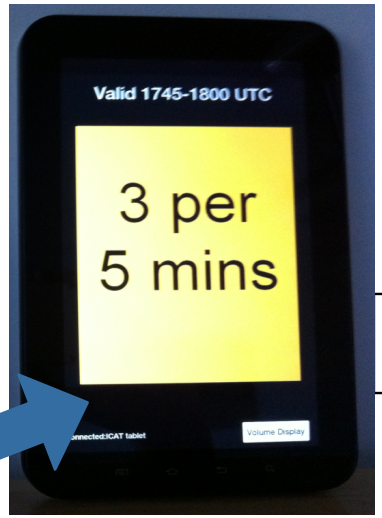
PARTNER
10 YEARS
2003-2013

- Suggest pushback rate (color-coded cards or a tablet display)

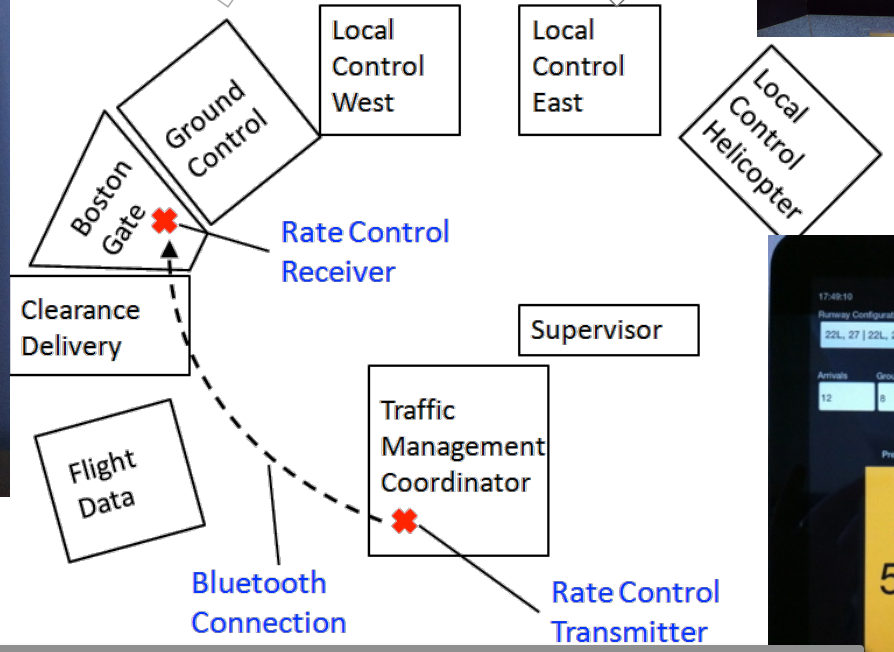


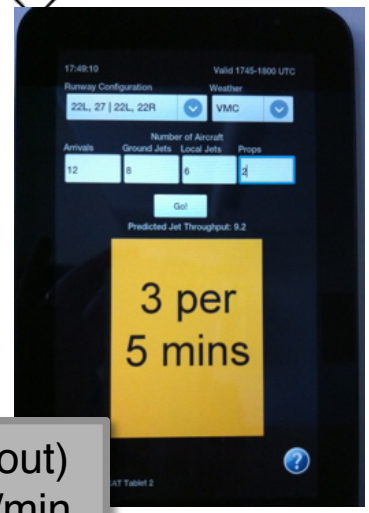






Alternative display modes



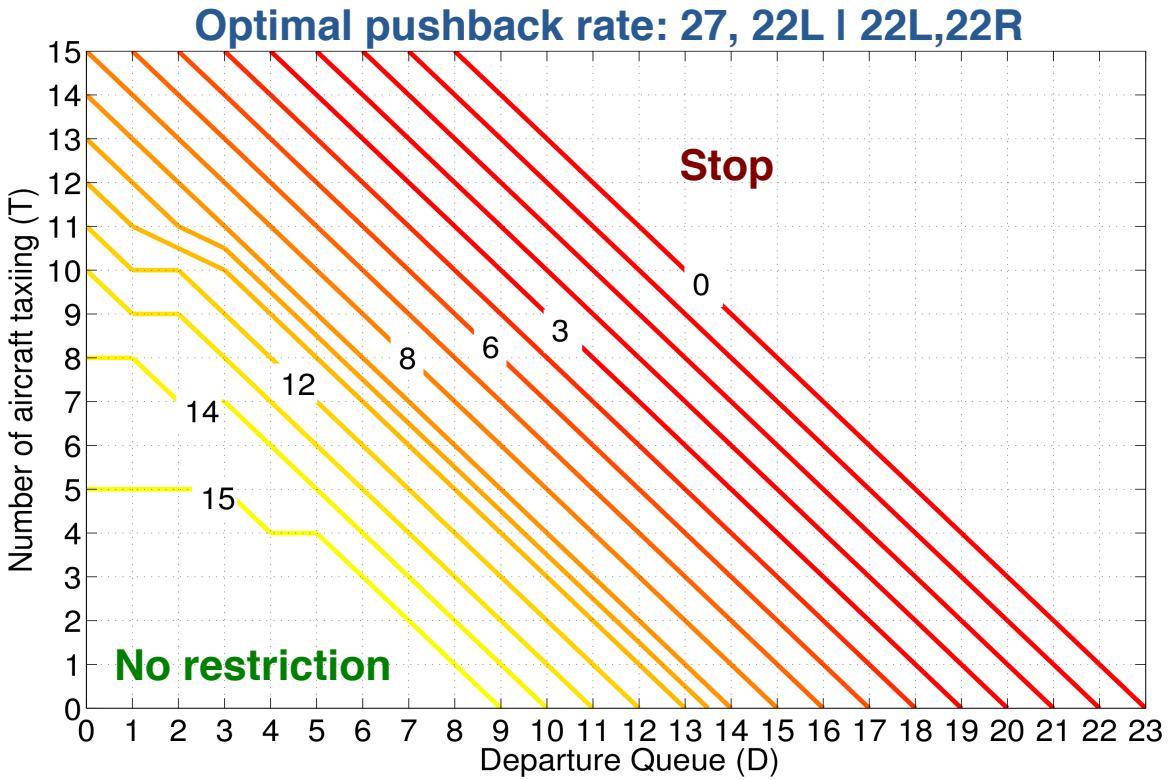


- Pushbacks in current time interval can be released (grayed out)
- Unused rate is carried over to the next time interval, up to 2/min
- Pushbacks in future time intervals can be reserved (angled)
- Pushbacks can be reserved for the following 15-min time period

Designing Control Strategy

PARTNER
10 YEARS
2003-2013

- Formulate a dynamic control problem that recommends pushback rate to maintain departure throughput, given loading of taxiway and runway queues
  - Model runway queuing process and system dynamics
  - Optimal pushback rate to balance runway throughput and congestion



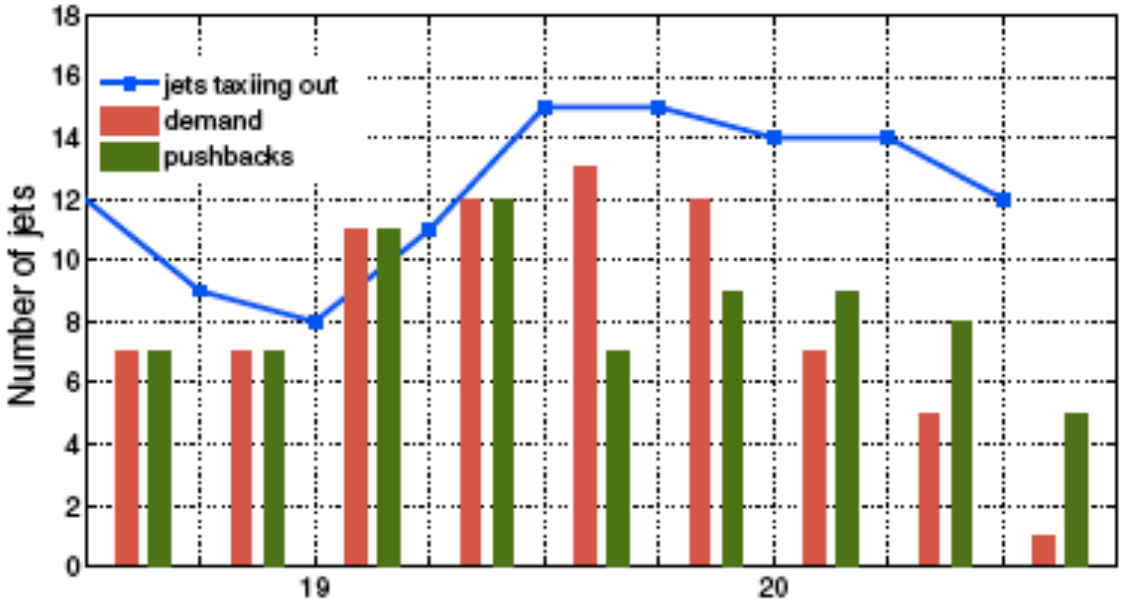
Simaiakis and Balakrishnan, American Control Conf., 2012.

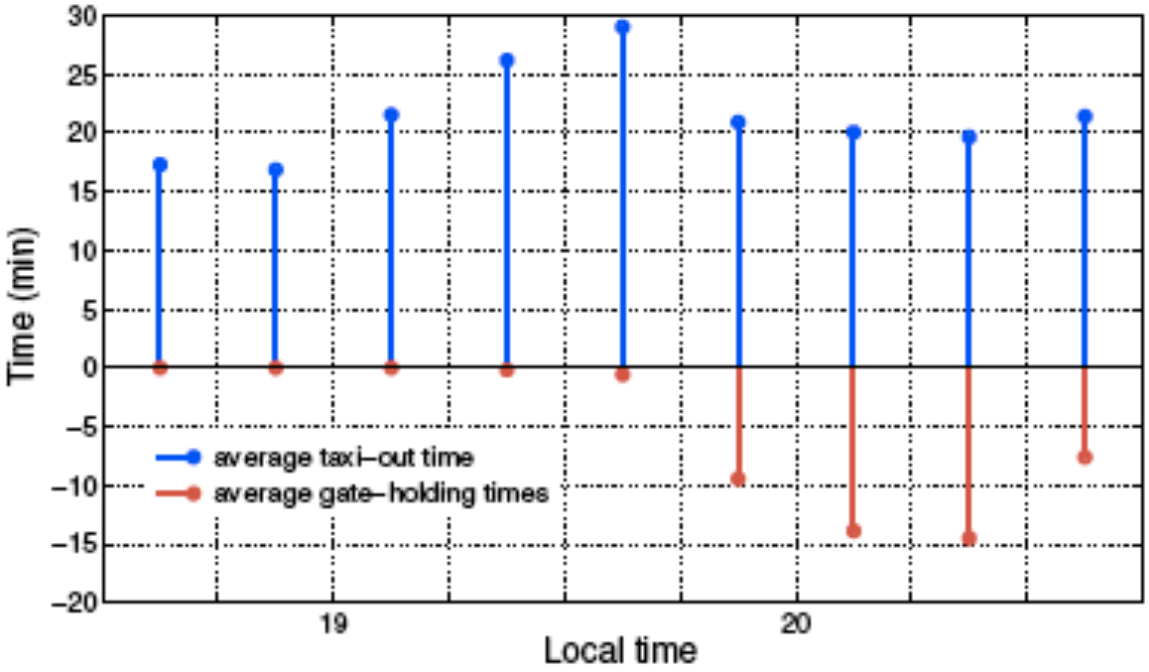
N Control Demonstration
Boston Logan (2010-2011)

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2003-2013



Sample Test Results: 7/21/2011





Simaiakis and Balakrishnan, American Control Conf, 2012.

BOS field test results

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10 YEARS
2003-2013

- Aug-Sep`10 & Jul-Aug`11
- 4PM-8PM departure push
- Average gate-hold: 4.7 min
- 23-25 tons (6,600-7,300 gal) reduction in fuel burn
- **160–178 gallons decrease in fuel burn / gate-held flight**
- 71-79 tons CO_2 reduction
- Fair distribution of benefits among airlines
- 1 min gate-hold => 1 min taxi-out time savings
- Throughput maintained
- Positive stakeholder feedback

Configuration	# of gate holds	Taxi-out time savings (min)
27, 22L I 22R	63	256
27, 32 I 33L	34	114
27, 32 I 33L	8	38
27, 22L I 22R	45	295
27, 22L I 22R	19	42
27, 22L I 22R	11	23
27, 32 I 33L	11	24
27, 32 I 33L	56	210
2010	**247**	**1003 min = 16.7 hours**
27, 22L I 22R	14	28
27, 22L I 22R	42	384
27, 22L I 22R	50	290
4L, 4R I 4L, 4R,9	11	13
4L, 4R I 4L, 4R,9	7	13
27, 22L I 22R	6	9
27, 22L I 22R	12	23
2011	**142**	**760 min = 12.7 hours**

Contributors

PARTNER
10 YEARS
2003-2013

- **MIT:** Prof. John Hansman, Prof. Hamsa Balakrishnan, Luke Jensen, Jean-Marie Dumont & Jonathan Lovegren, Ioannis Simaiakis, Harshad Khadilkar
- **MIT Lincoln Laboratory**: Dr. Tom Reynolds, Joe Venuti, Lanie Sandberg & Yari Rodriguez
- **Purdue University:** Prof. Karen Marais, Tiffany Le, Delri Muller & Payuna Uday
- **Georgia Tech:** Prof. John-Paul Clarke and students
- **Federal Aviation Administration:** Pat Moran, Steve Urlass

PARTNER RESEARCH, 2003 – 2013
PUBLIC SYMPOSIUM

Fuels and Emissions

Session Chair: Jim Hileman

Opinions, findings, conclusions and recommendations expressed in this material are those of the author(s)
and do not necessarily reflect the views of PARTNER sponsor organizations.

PARTNER
Partnership for Air Transportation
Noise and Emissions Reduction

PARTNER RESEARCH, 2003 – 2013
PUBLIC SYMPOSIUM

PARTNER
Leading the Way
in
Alternative Fuels Emissions Characterization

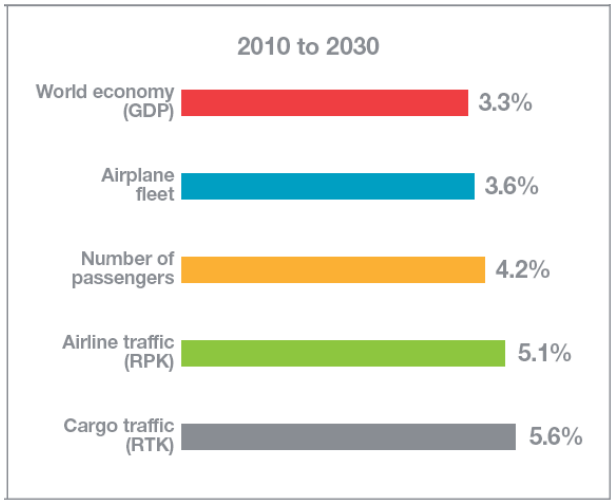
Project manager: Carl Ma, FAA
Principle investigator: Phil Whitefield, Missouri University of Science and Technology

Opinions, findings, conclusions and recommendations expressed in this material are those of the author(s)
and do not necessarily reflect the views of PARTNER sponsor organizations.

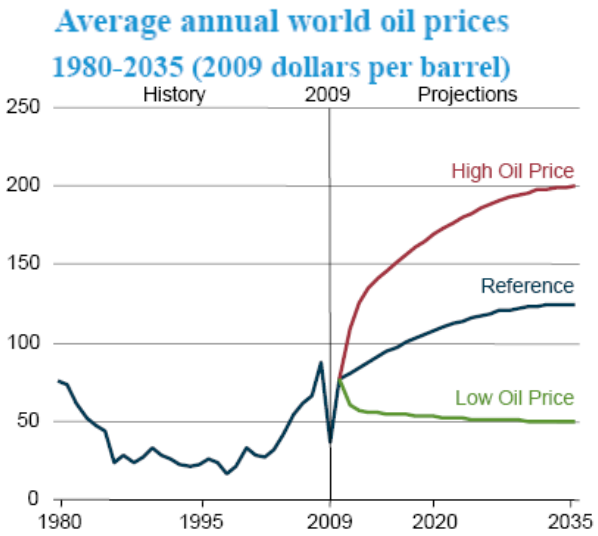
PARTNER
Partnership for Air Transportation
Noise and Emissions Reduction

Motivation

- Growth in commercial air traffic, rising costs of fuel, an increasing desire to enhance the security of energy supply, and potential environmental benefits have driven feasibility and viability assessment studies of alternative renewable fuels for commercial aviation applications.
- The objectives of project 20 are to collect emissions data and assess exhaust emissions from engines running on alternative fuels as compared with conventional fuel.
- These data will provide the essential specific information needed to evaluate environmental benefits from the use of alternative fuels and to demonstrate their viability for long term environmental sustainability in an uncertain energy future.



Source: Boeing Current Market Outlook 2011-2030



Source: US EIA Annual Energy Outlook 2011

Objectives

- Long-term
  - Provide comprehensive data on the impact of candidate alternate fuels on PM and HAP emissions from engines currently operating in the commercial fleet.

- Near term
  - The primary objective of this project is to examine and quantify any reductions in PM and HAP emissions from engines burning 100% alternative FT and Bio-fuels and various blends as compared to conventional JET A, JET A-1, and JP-8 fuels
  - A secondary objective is to obtain and compare PM and HAPs emissions data from engines burning conventional fuels. This second objective will further populate data for the PM-HAPs emissions research database.

Outcomes and Practical Applications

PARTNER

- Deliverables [Final report and data set]
  - Findings on PM (and HAPS) emissions data collected at the engine exit plane and at various downstream locations from commercial transport engines (from the CFM56 family of engines) burning pure 100% alternate fuels (FT and HEFA fuels) and various blends (e.g., 20%, 40%, 50%, etc.) of alternate fuels and conventional fuels.
  - Additional PM (and HAPs) emissions data from commercial transport engines burning conventional fuels i.e. Jet A, Jet A-1, JP8.

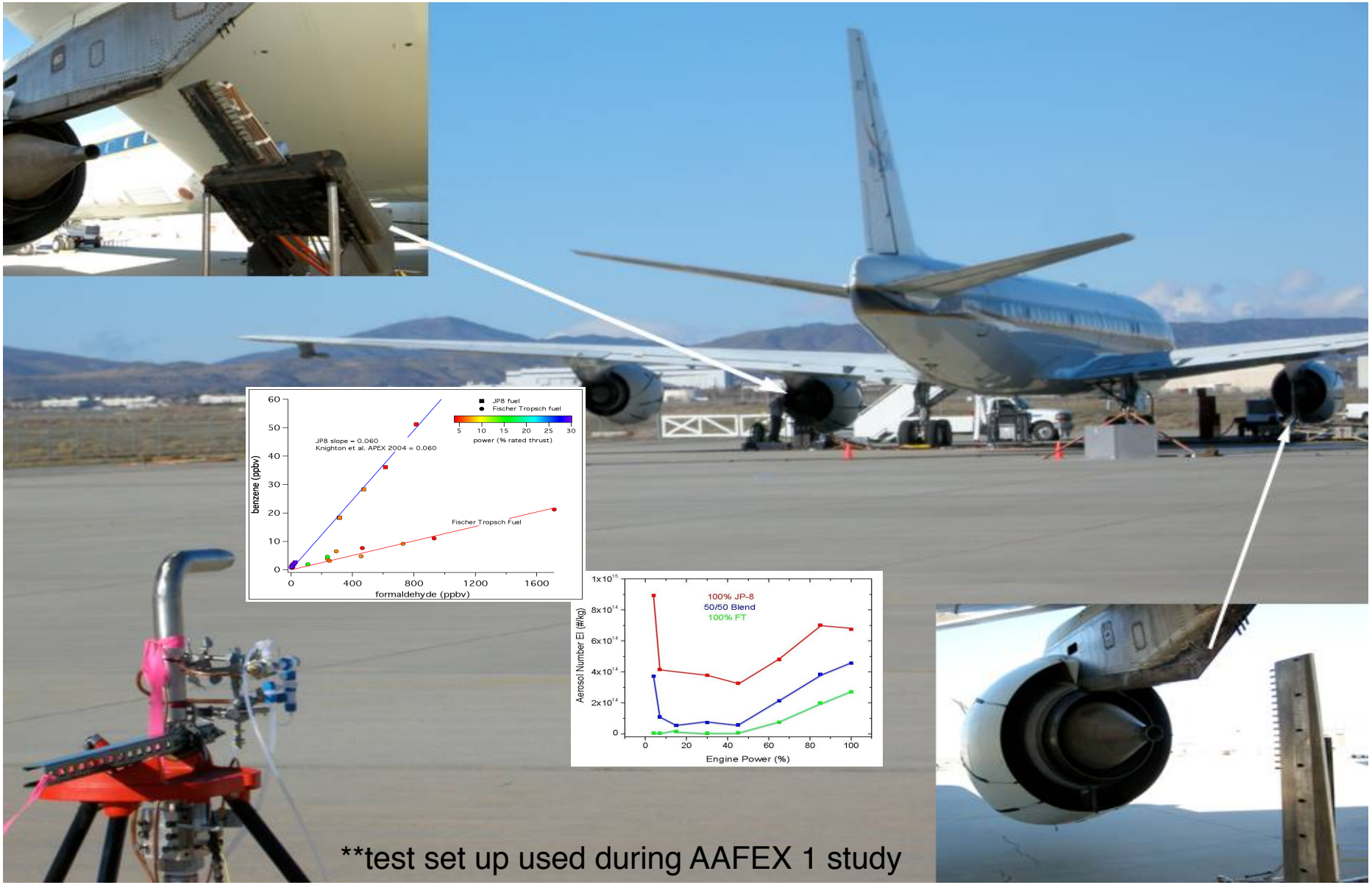
- Practical applications
  - Provides engine specific data for environmental impact analyses and for assessing fuel effects on emissions characteristics
  - Where will this information be used?
    - Development of Environmental Assessments (EA's) and Environmental Impact Statement (EIS) for airport construction permit
    - Selection criteria for potential candidate alternative fuels
  - When will this information be used?
    - In projections anticipating future adoption of alternative aviation fuels
  - Who do you anticipate will use it?
    - Regulatory agencies, Airports, CAAFI, fuel producers, airframe and engine manufacturers

Alternative Fuels Emissions Testing

PARTNER

Date	Location / Campaign	Engine(s)	Fuels
Nov / Dec 2007	GE Engine Test Facility, Peebles, OH GE Alt Fuels Study	CFM56-7B	▪ Jet A, Jet A1 ▪ 20:80 FAME:Jet A1 ▪ 40:60 FAME:Jet A1 ▪ 50:50 FT (gTL): Jet A1 ▪ 100%FT (gTL)
Jan / Feb 2009	NASA Dryden Aircraft Operations Facility, Palmdale, CA AAFEX	CFM56-2C1 GTC 85-98CK APU	▪ JP8 ▪ 100% FT (gTL) ▪ 50:50 gTL: JP8 ▪ 100% FT (cTL) ▪ 50:50 cTL:JP8
Sep /Oct 2009	Low Carbon Combustion Centre, Sheffield, UK Conducted under project # 34	Recommissioned APU	▪ Jet A1 ▪ 100% FT (cTL) ▪ 100% FT (gTL), ▪ 50:50 gTL: Jet A1 ▪ Biodiesel ▪ Diesel
Mar / Apr 2011	NASA Dryden Aircraft Operations Facility, Palmdale, CA AAFEX II	CFM56-2C1	▪ JP8 ▪ Tallow HRJ ▪ 50:50 HRJ:JP8 ▪ FT (cTL) ▪ FT + THT

Approach

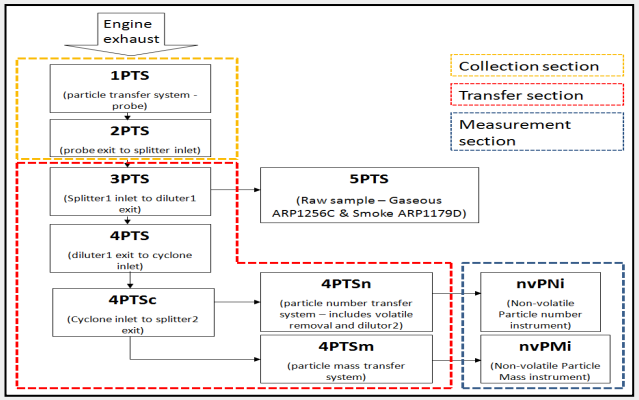


**test set up used during AAFEX 1 study

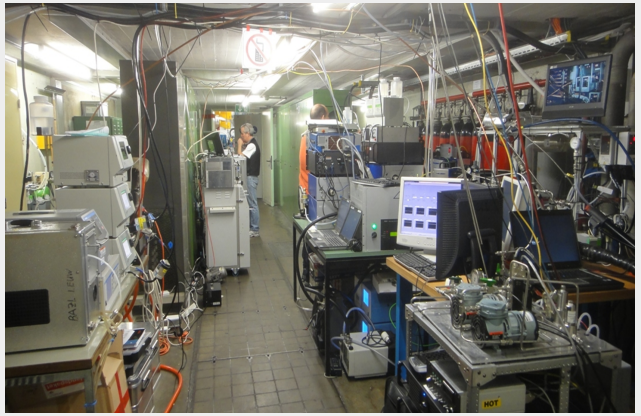
Approach

Design, Assemble, Validate, and Deploy an ARP compliant mobile reference non-volatile PM system

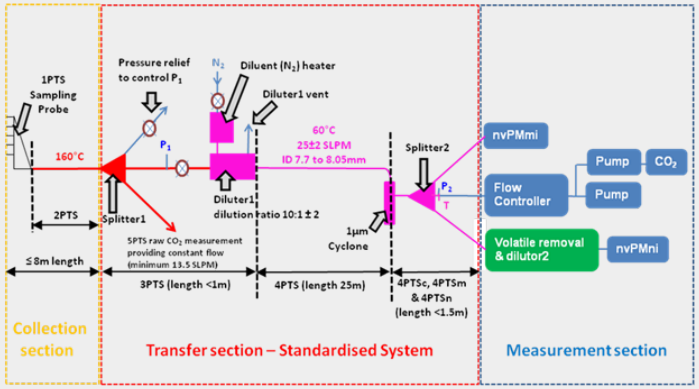
Concept



Validate



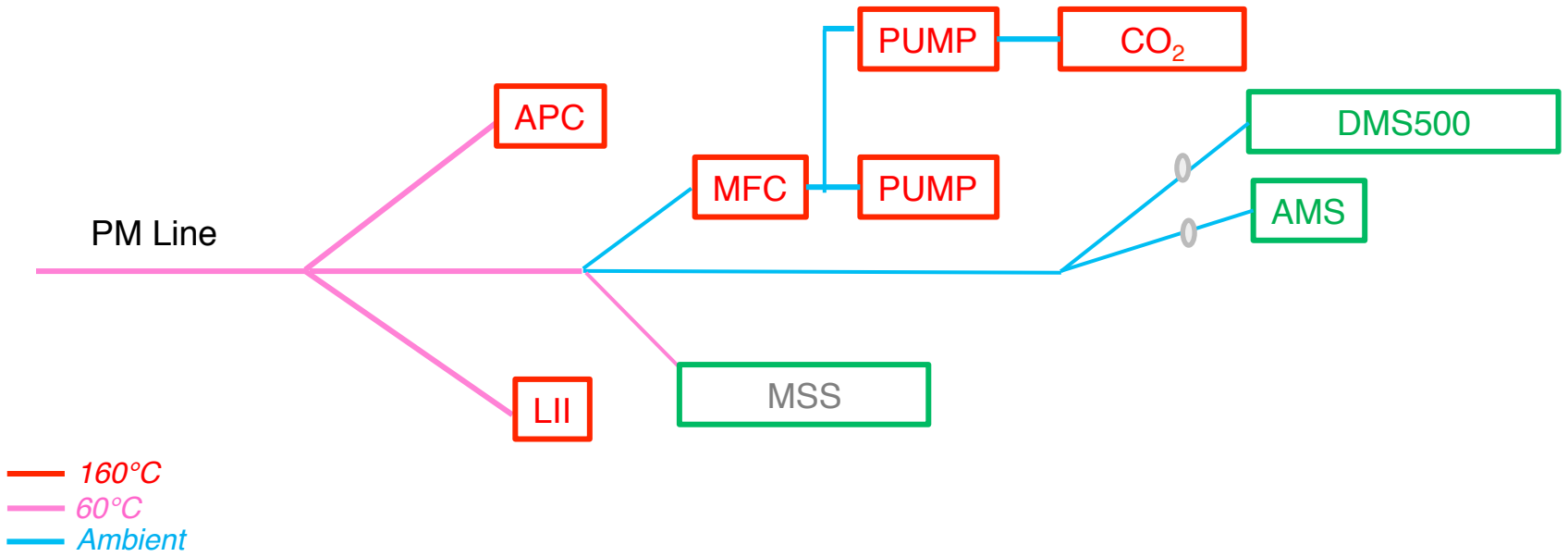
Design and Assemble



Deploy



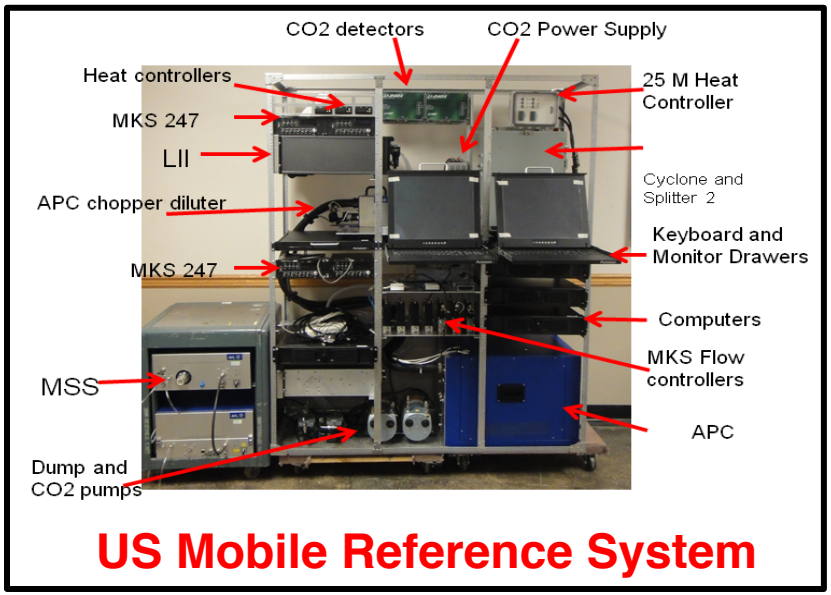
System Configuration (ARP + ancillary instruments)



Implementation of Draft Working Document Sampling Reference Systems (Stationary and Mobile)

PARTNER

CONCEPT



US Mobile Reference System

OEM/ Other Probe

Excess Flow Dump Line

Annex-16 Line

Splitter1

Diluter & Spill

25 m Sample Line

Control and Diluent Lines

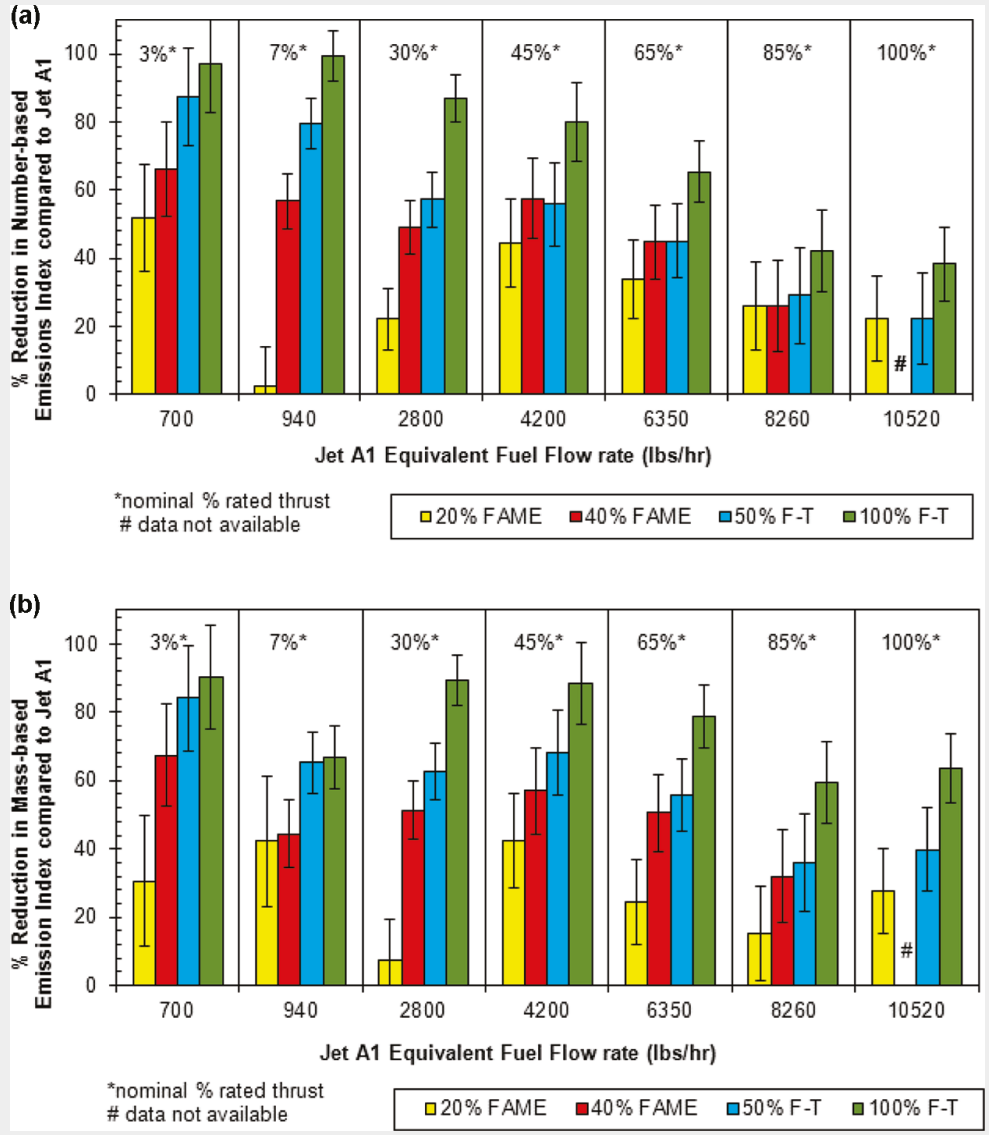
19" rack mounted

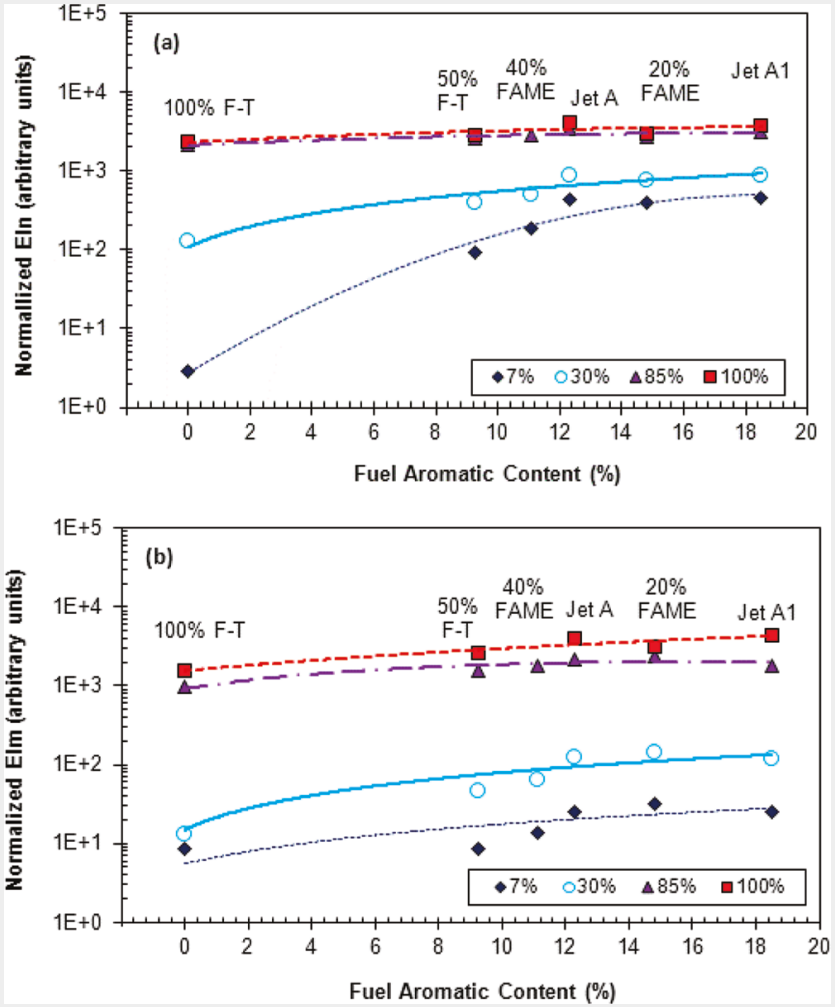
- System Control
- CO_2 Analyzers
- Mass Analyzer
- CPC (Number)
- VPR with Diluter
- Cyclone, Splitter2, Pumps

1 PTS & 2PTS | 3PTS | 4PTS | 4PTSc, 4PTSm, 4PTSn, & Measurement Section

Robust mobile system that can be deployed anywhere in US and overseas

GE Alt Fuels Study





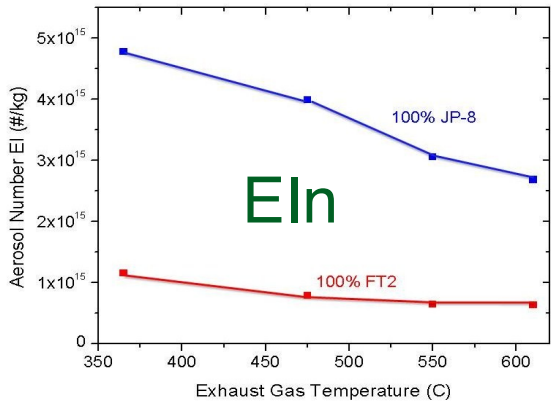
Source: Lobo et al., Environ. Sci. Technol. 2011, 45, 10744–10749

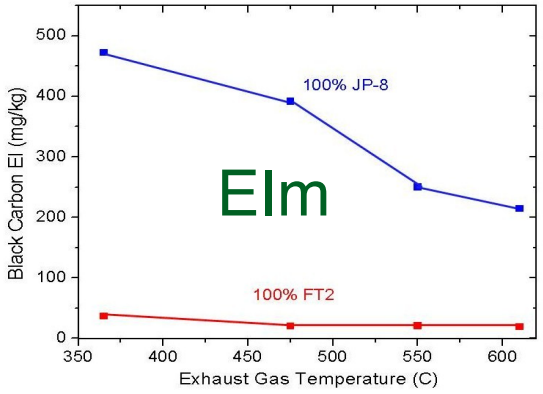
AAFEX

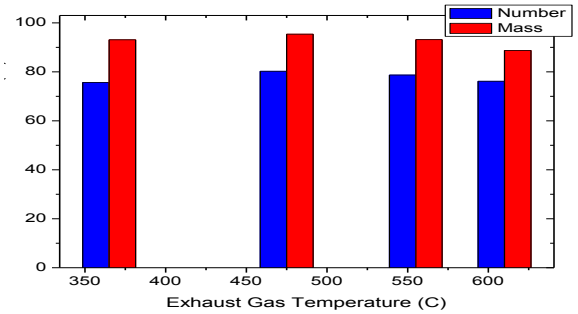
PARTNER

APU vs. CFM56 Emissions

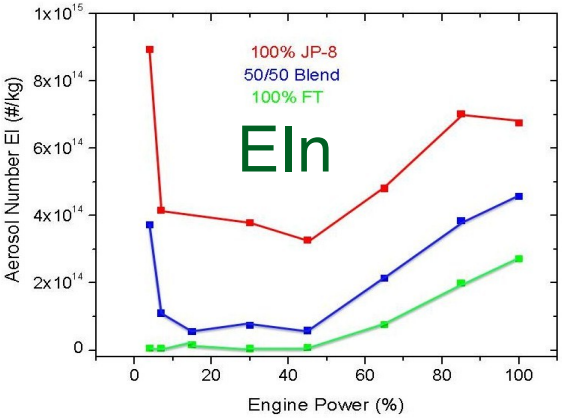
APU

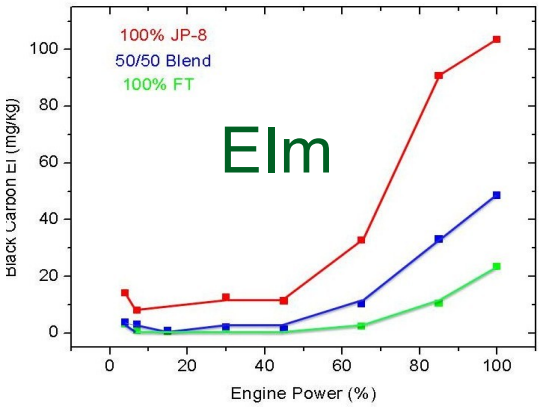


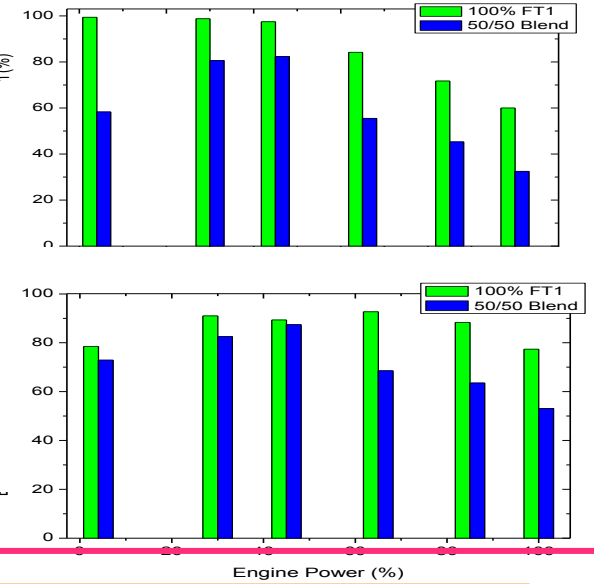




CFM56







- APU emits 25x more black carbon per kg fuel at idle than the CFM56 engine
- APU emits 5x the number of particles per kg fuel at idle than the CFM56 engine
- Mass emissions 90% lower when burning FT fuel

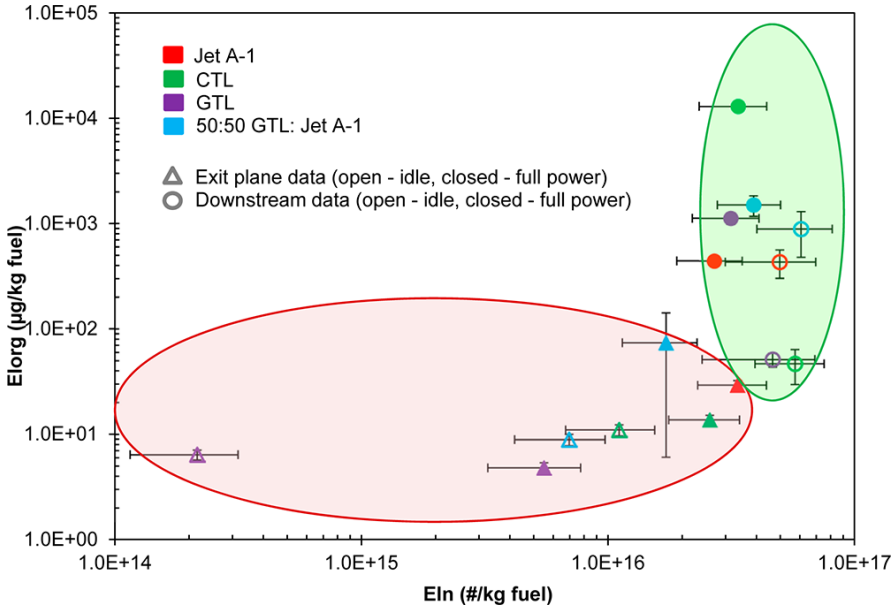
Sheffield APU Study

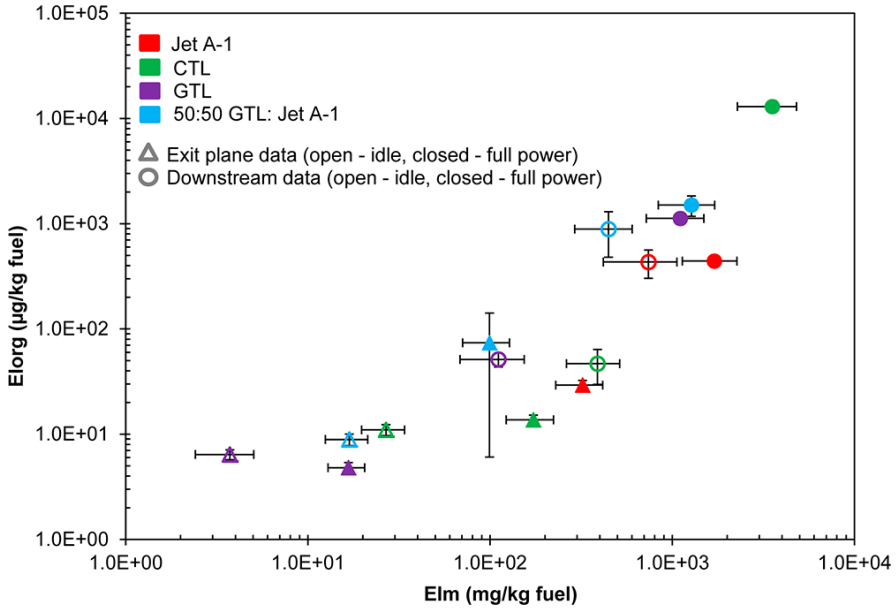
Conducted under project #34

Exit plane

- Greatest reductions in nvPM emissions were observed at the idle condition
- For EIn at idle, dramatic reductions of 99% were observed for the GTL fuel, with 60% reduction for 50:50 GTL: Jet A-1 and 42% reduction for CTL
- The average EIm reductions compared to Jet A-1 at idle and full power were in the following order: GTL (90%) > 50:50 GTL:Jet A-1 (72%) > CTL (65%).

Downstream



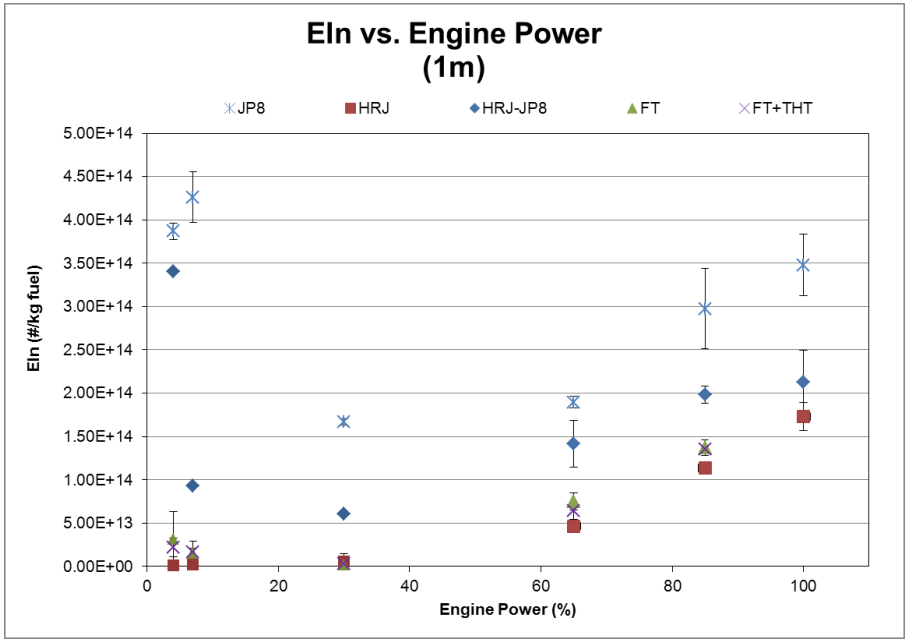


Source: Lobo et al., Environ. Sci. Technol. 2012, DOI: 10.1021/es301898u

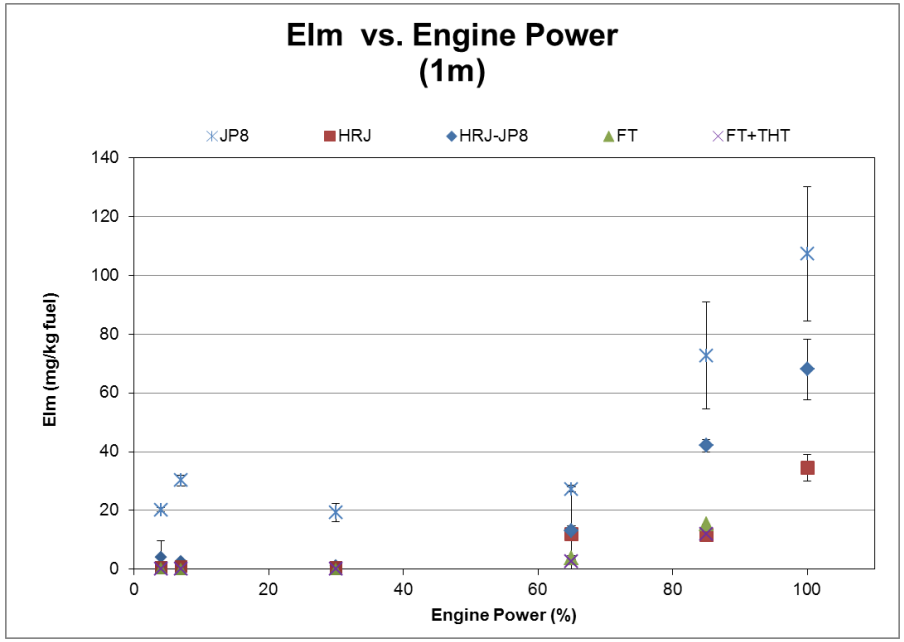
AAFEX II

PARTNER

Engine exit plane PM Emissions



Greatest emissions indices reductions with 100% alternative fuels

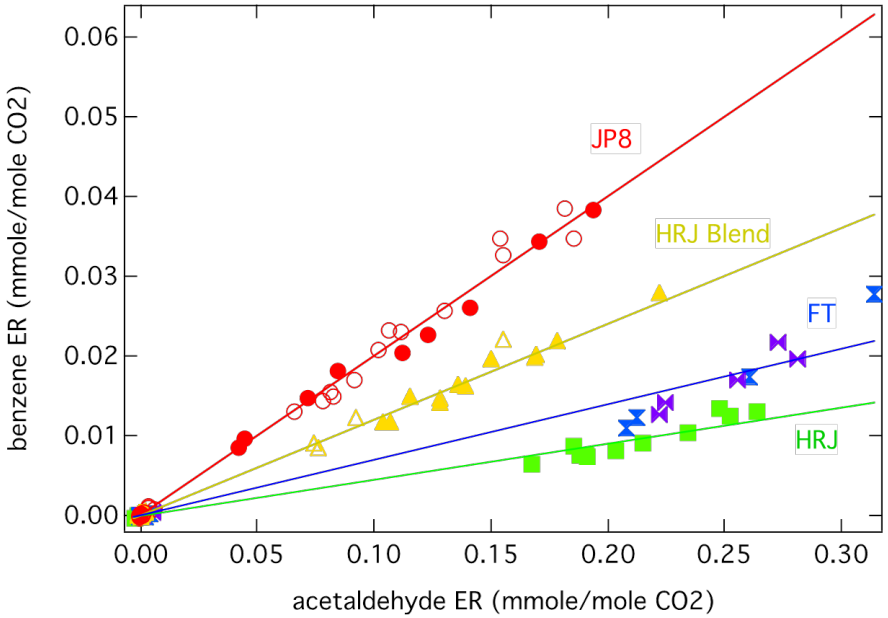


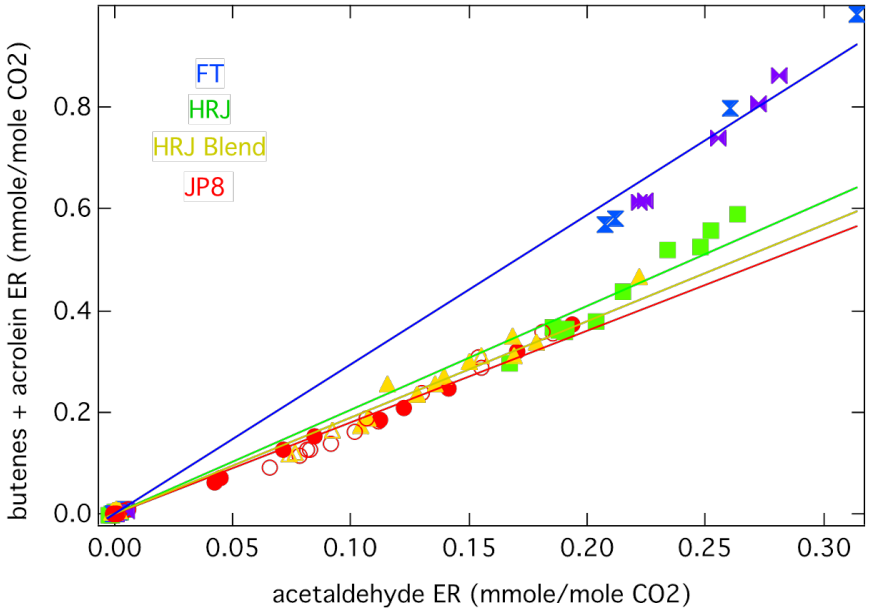
Significant reductions in PM number- and mass-based emission indices are observed for the alternative fuels compared to JP8

AAFEX II

PARTNER

HAPs Emissions Scaling: Fuel Effects

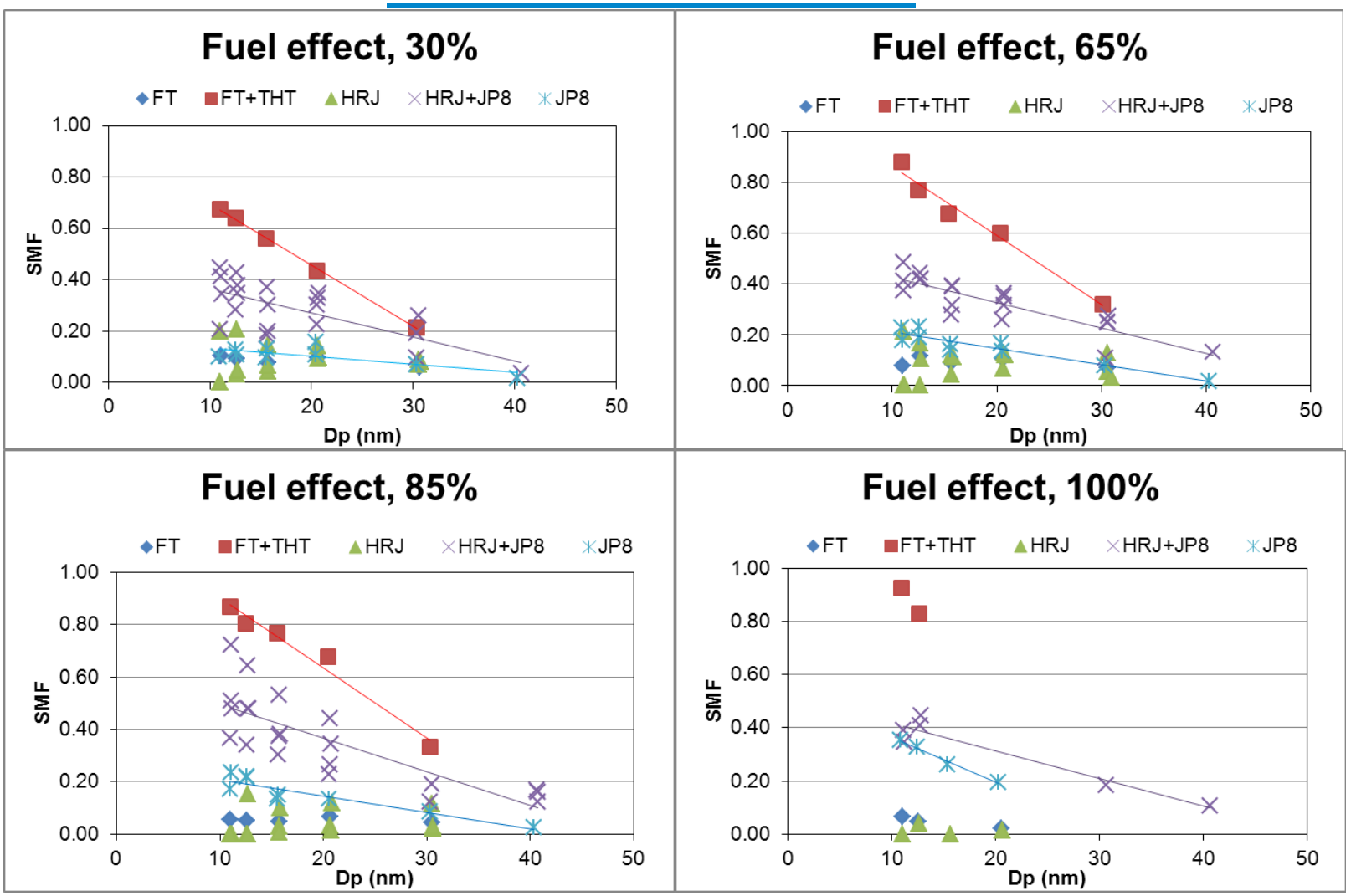




AAFEX II

PARTNER

Soluble Mass Fraction

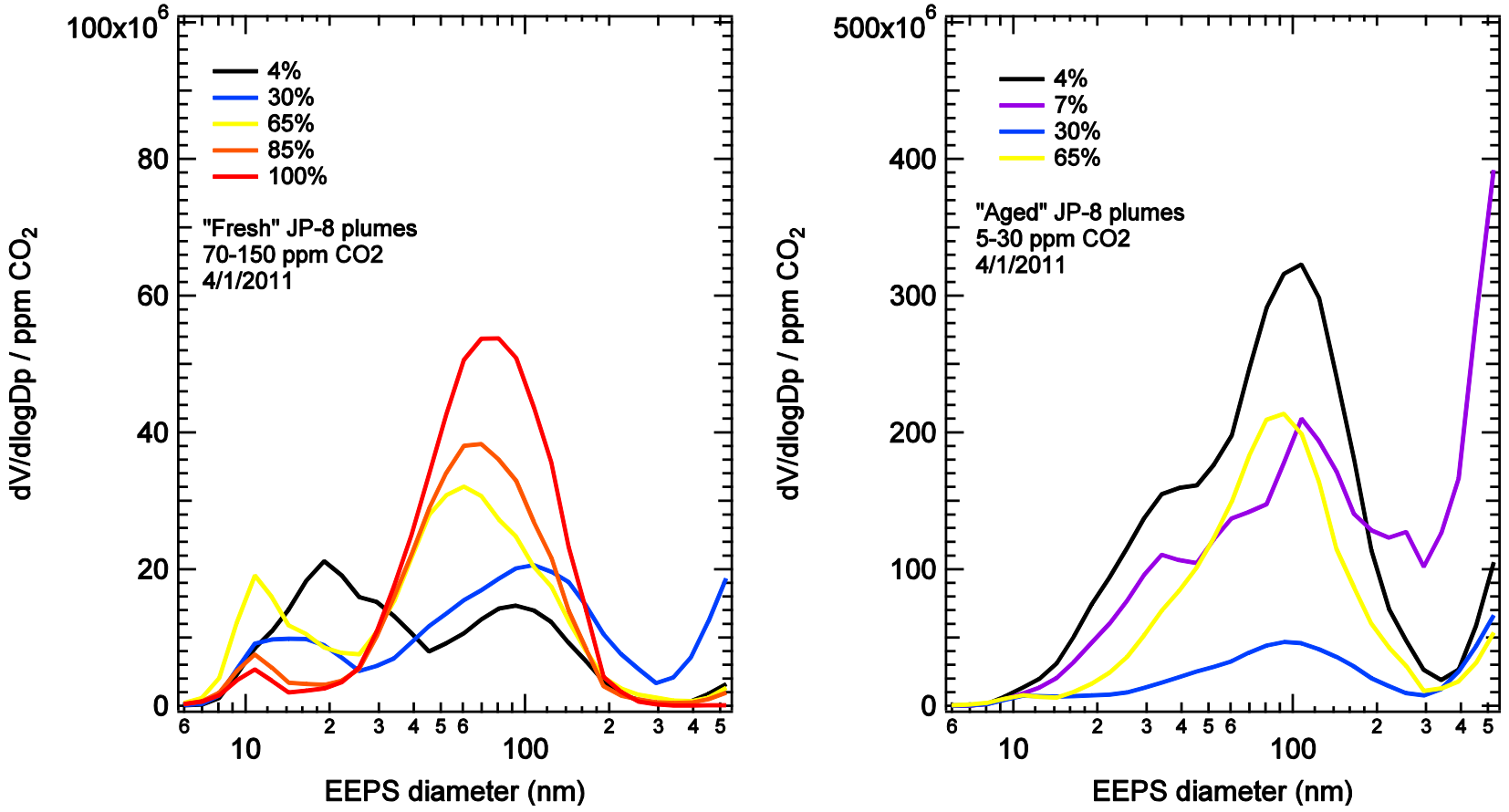


Soluble Mass Fraction (SMF) increases with fuel sulfur content and engine power condition, and decreases with particle diameter

AAFEX II

PARTNER

"Fresh" vs. "Aged" Plumes



Comparisons of the EEPS size distributions obtained for "fresh" and "aged" plumes.

As expected for "fresh" plumes, the ratio of Soot Mode (SM) to Nucleation Mode (NM) increases monotonically with increasing power. Interestingly, the SM at 4 and 30% appears larger than at 65, 85, or 100%. The "aged" plumes no longer have a highly distinguished NM, evidence of nucleation mode growth and coagulation

Summary of Alternative Fuel Emissions Testing

- Significant reductions in nvPM emissions, especially at idle power conditions
- Small to no change in NOx emissions with alternative fuels
- nvPM Emissions reductions attributed to alternative fuel properties, specifically lower fuel aromatic content
- Sulphate PM Emissions reductions in the near and far field attributed to extremely low/negligible fuel sulfur content (<20 ppm)

Interfaces and Communications

- External
  - Publications
    - Kinsey, J. S., Timko, M.T., Herndon, S. C., Wood, E. C., Yu, Z., Miake-Lye, R. C., Lobo, P., Whitefield, P., Hagen D., Wey, C., Anderson, B., Beyersdorf, A., Hudgins, C., Thornhill, L., Winstead, E., Howard, R., Bulzan, D., Tacina, K., Knighton, W. B., "Determination of the Emissions from an Aircraft Auxiliary Power Unit (APU) during the Alternative Aviation Fuels EXperiment (AAFEX)," *Journal of the Air and Waste Management Association* (2012), Vol. 62, No. 4, 420-430.
    - Lobo, P., Hagen, D.E., and Whitefield, P.D., "Measurement and analysis of Aircraft Engine PM Emissions downwind of an active runway at the Oakland International Airport," *Atmospheric Environment* (2012), Vol. 61, 114-123.
    - Lobo , P., Rye, L., Williams, P. I., Christie, S., Uryga-Bugajska, I., Wilson, C. W., Hagen, D. E., Whitefield, P. D., Blakey, S., Coe, H., Raper, D., and Pourkashanian, M., "Impact of Alternative Fuels on Emissions Characteristics of a Gas Turbine Engine - Part 1: Gaseous and Particulate Matter Emissions," *Environmental Science and Technology* (2012), DOI: 10.1021/es301898u
    - Williams, P. I., Allan, J.D., Lobo, P., Coe, H., Christie, S., Wilson, C., Hagen, D., Whitefield, P., Raper, D., and Rye, L. "Impact of Alternative Fuels on Emissions Characteristics of a Gas Turbine Engine - Part 2: Volatile and Semivolatile Particulate Matter Emissions," *Environmental Science and Technology* (2012), DOI: 10.1021/es301899s
  - Other groups you are working with
    - VOLPE - Benefits Assessment (FAA AEE's mechanism for projecting expected energy, emissions, and noise performance nationwide)
- Within PARTNER
  - Other projects: 11, 16, 27, 28, 47

PARTNER RESEARCH, 2003 – 2013

PUBLIC SYMPOSIUM

FUELS AND EMISSIONS

Sustainability of alternative fuels for aviation

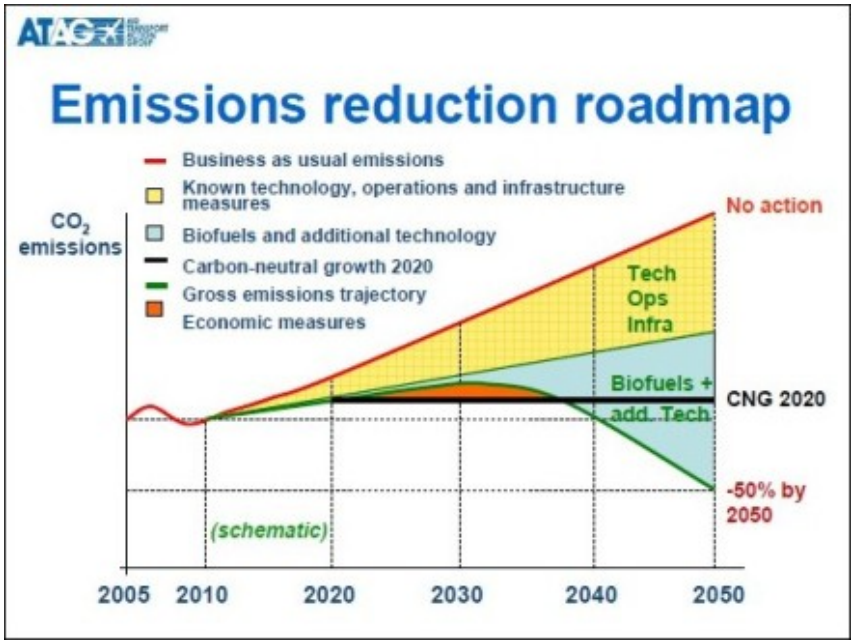
Presented by: Steven Barrett, MIT

Opinions, findings, conclusions and recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of PARTNER sponsor organizations.

10th Year Public Symposium
March 1, 2013
Costa Mesa, CA

PARTNER
Partnership for Air Transportation Noise and Emissions Reduction

Motivation



Source: ATAG

Environmental motivation:

- The air transport industry as well as governmental agencies are committed to ambitious CO_2 reduction goals
- Biofuels will play an important role in the mitigation strategy
- There may be additional benefits in terms of public-health impacts due to lower exhaust emissions

Economic motivation

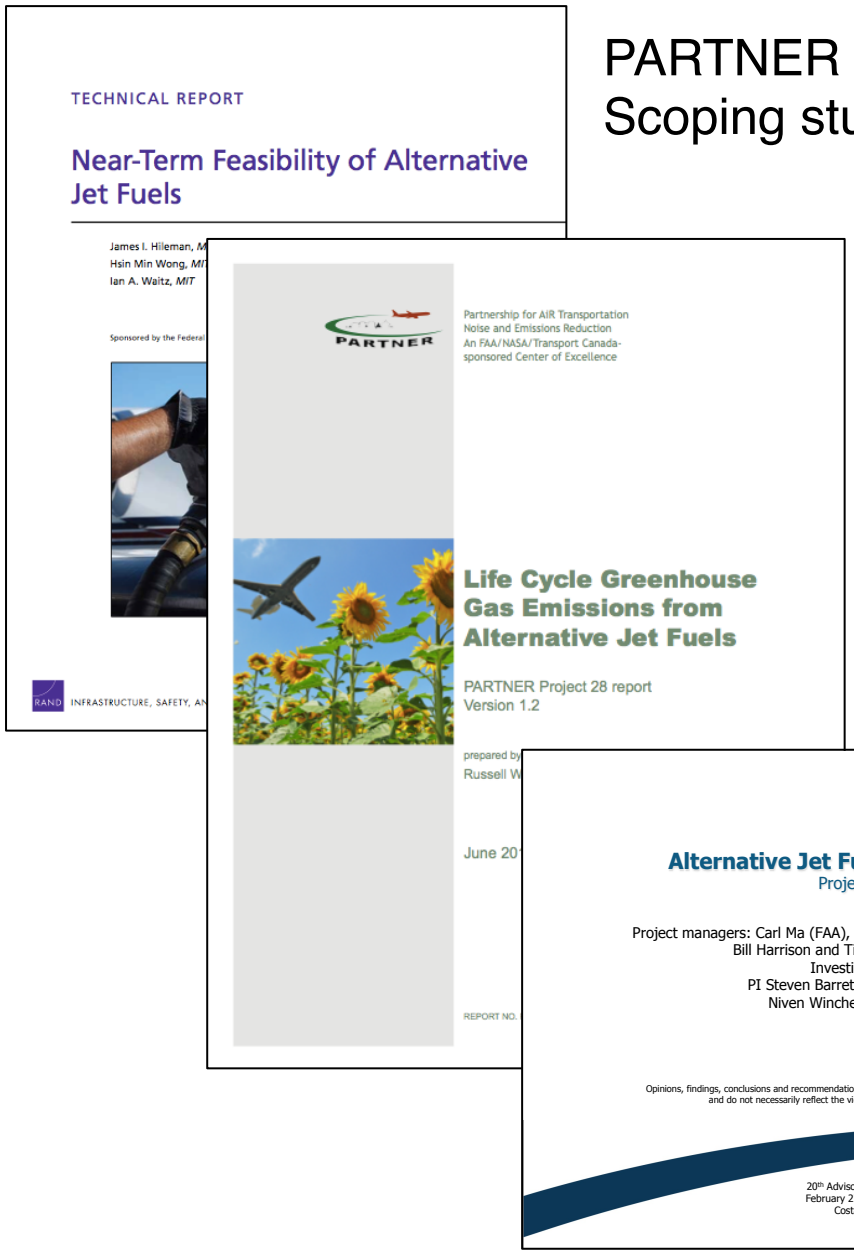
- The use of alternative fossil and renewable fuels can help to diversify energy supplies and increase energy independence

Challenge

PARTNER
10 YEARS
2003-2013

- Alternative fuels need to be compatible with existing aircraft because of long replacement cycles (average aircraft utilization: ~25 years) and >$1 trillion assets in existing aircraft
- Alternative fuels need to be economically viable – otherwise airlines will not use it
- There may be unintentional consequences involved in using alternative fuels with regard to water usage (quantity and quality) and direct or indirect changes in land use

Research



PARTNER Project 17:
Scoping study on feasibility of alternative jet fuels

PARTNER Project 28:
Screening-level analysis of environmental sustainability of alternative aviation fuels

PARTNER Project 47:
Focus on trade-offs among metrics and usages, developing the big-picture view of costs and benefits

Research

PARTNER
10 YEARS
2003-2013

When we started (Jan 2008):

- Policies on alternative fuel usage kicking in
  (RFS 2, Section 526 EISA, later: FAA renewable fuels goal)
- Significant knowledge about ground alternative fuels, but:
- Overall knowledge on sustainability of alternative jet fuels low
- State of lifecycle GHG methodology for alternative jet fuels unsatisfactory
- No comprehensive and open tool available for assessing lifecycle GHG emissions of alternative jet fuels

Pathway scope

PARTNER
10 YEARS
2003-2013

Source	Feedstock	Recovery	Processing	Final Product
Petroleum	Conventional crude	Crude extraction	Crude refining	Jet A / Diesel
	Conventional crude	Crude extraction	Crude refining	ULSJ/D
	Canadian oil sands	Bitumen mining/ extraction and upgrading	Syncrude refining	Jet A / Diesel
	Oil shale	In-situ conversion	Shale oil refining	Jet A / Diesel
Natural gas	Natural gas	Natural gas extraction and processing	Gasification, F-T reaction and upgrading (with and without carbon capture)	SPK Jet / Diesel Fuel (FTJ/FTD)
Coal	Coal	Coal mining	Gasification, F-T reaction and upgrading (with and without carbon capture)	SPK Jet / Diesel Fuel (FTJ/FTD)
Coal and Biomass	Coal and Biomass	Coal mining and biomass cultivation	Gasification, F-T reaction and upgrading (with and without carbon capture)	SPK Jet / Diesel Fuel (FTJ/FTD)
Biomass	Biomass – switchgrass[1,2] – corn stover[1] – woody[1,3] – corn[2] – sugarcane[2]	Biomass cultivation	[1]Gasification, F-T reaction & upgrading [2](Advanced) fermentation & hydroprocessing [3]Aqueous-phase processing	SPK Jet / Diesel Fuel ([1]FTJ/FTD) ([2]AFJ/AFD)
	Renewable oil – soybeans – palm – algae – jatropha – rapeseed – salicornia – camelina	Biomass cultivation and extraction of plant oils	Hydroprocessing	SPK Jet / Diesel Fuel (HEFA-J/HEFA-D)

Metric scope

PARTNER
10 YEARS
2003-2013

Source	Feedstock		Processing	Final Product
Petroleum	Conventional crude	C	de	Jet A / Diesel
	Conventional crude	Cr	Crude	ULSJ/D
	Canadian oil sands	Bitumen mi extraction a upgrading	Syncr	Jet A / Diesel
	Oil shale	situ conversion	Sha refining	Jet A / Diesel
Natural gas	Natural	N	fication, F-T nd without	SPK Jet / Diesel Fuel (FTJ/FTD)
Coal	Coal		d without	SPK Jet / Diesel Fuel (FTJ/FTD)
Coal and Biomass	Coal and Biomass	bio	fication, F-T with and without carbon capture)	SPK Jet / Diesel Fuel (FTJ/FTD)
Biomass	Biomass		[1]Gasification, F-T reaction & upgrading	SPK Jet / Diesel
Biomass	Renewable oil – soybeans – palm – algae – jatropha – rapeseed – salicornia – camelina	Biomass cultivation and extraction of plant oils	Hydroprocessing	SPK Jet / Diesel Fuel (HEFA-J/HEFA-D)

Water

Air Quality

Land

Climate

Sustainability

Production Costs

Assess sustainability with a broad set of **quantifiable** metrics

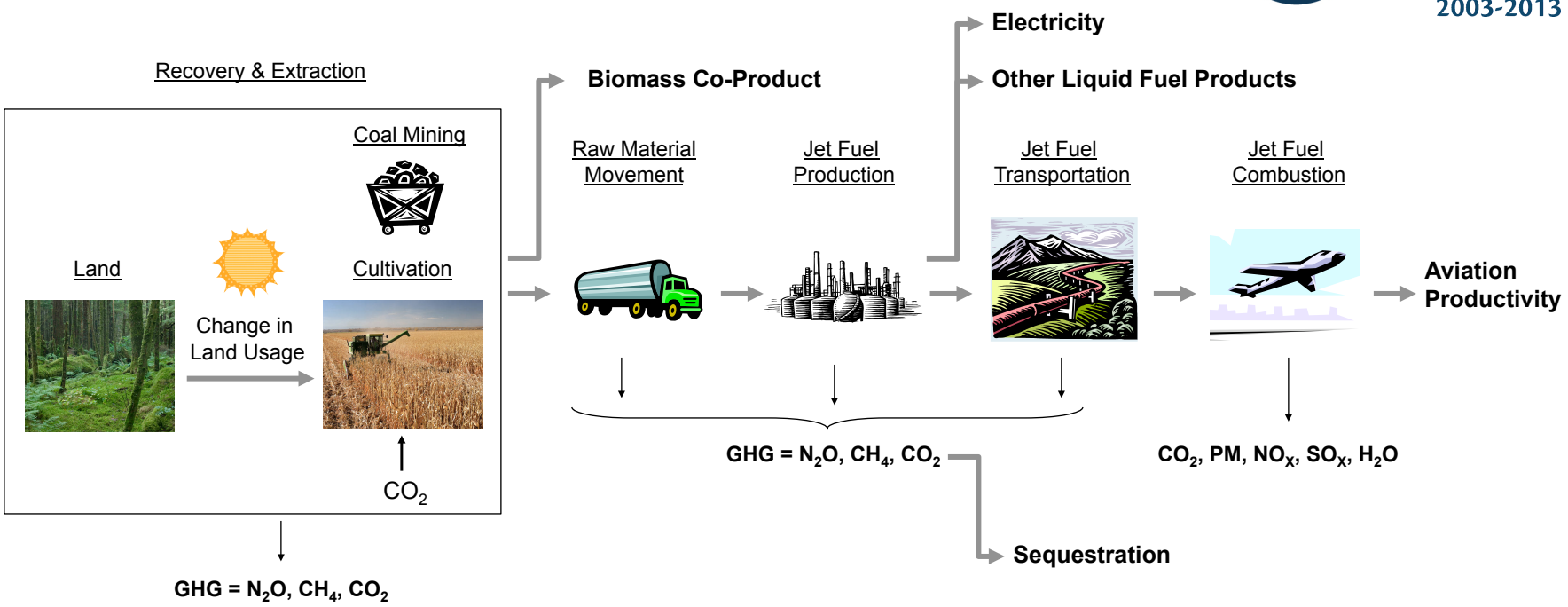
Practical applications

PARTNER
10 YEARS
2003-2013

- Guidance for policy makers and fuel purchasers on
  - Appropriate methodology for assessing climate impact of alternative jet fuels
  - Drivers of sustainability for different feedstock-to-fuel pathways and
  - GHG footprint of specific feedstock-technology set combinations

- Guidance especially valuable in the context of:
  - Renewable fuel standard eligibility
  - Compliance with Section 526 of Energy Independence and Security Act of 2007

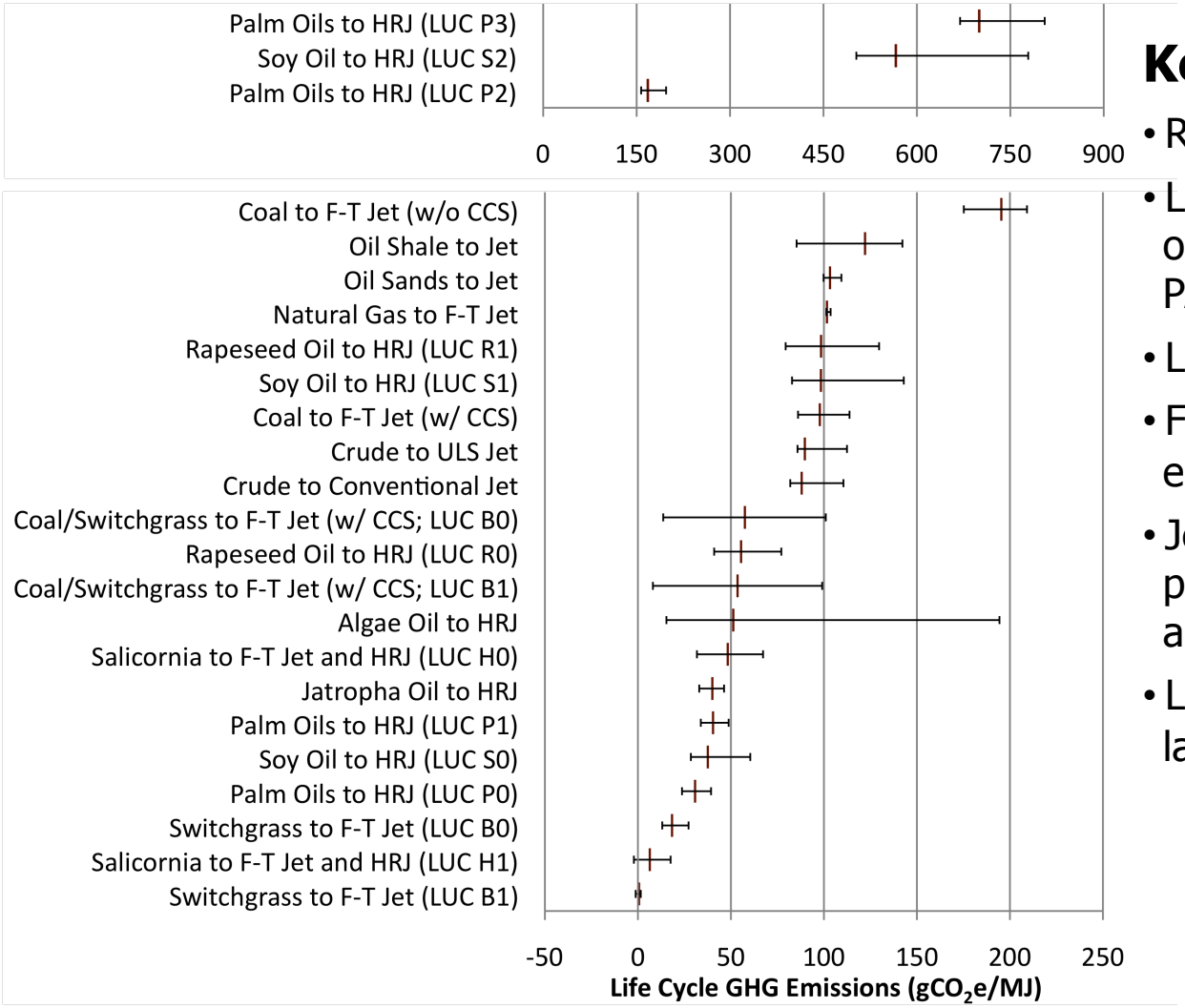
Approach



Worked with Argonne National Labs on GREET (The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation) Model

- GREET originally designed for ground transportation fuels
- Changed refining process to reflect jet fuel production
- Created many new feedstock-to-fuel pathways (e.g., oil shale, palm, jatropha, salicornia, camelina, switchgrass, algae) that were not in GREET

Outcomes (1 of 4)



Key Outcomes:

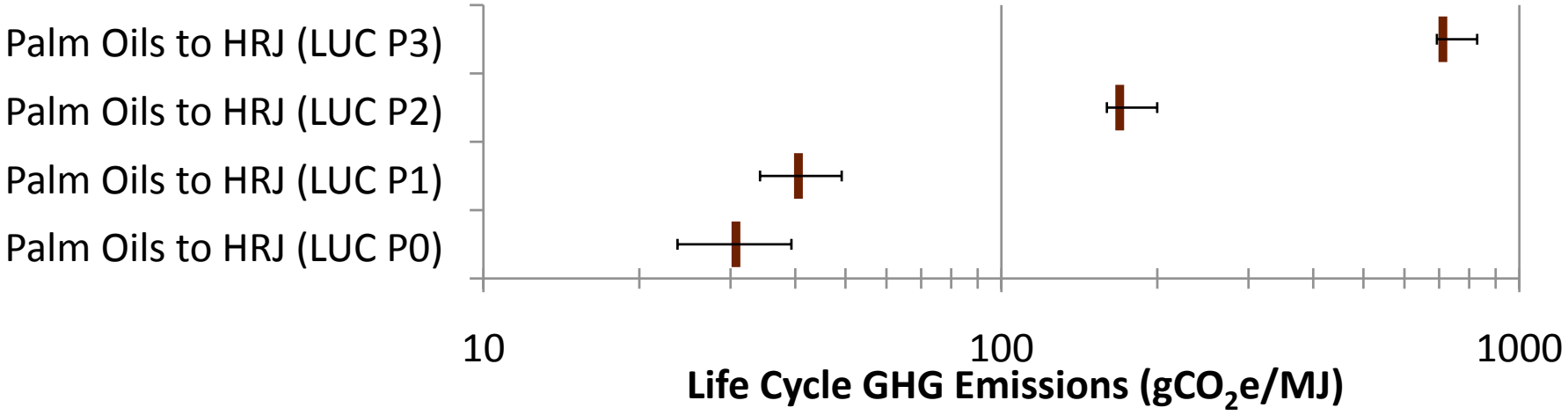
- Results from screening level study
- List here does not include all fuel options investigated under PARTNER
- Large variability in emissions
- Few biofuels have zero GHG emissions
- Jet fuel from conventional petroleum has lowest emissions among fossil fuels
- Land use change emissions have large impact on results

Source: Stratton et al (2010).

Outcomes (2 of 4)

PARTNER
10 YEARS
2003-2013

LUC P0: No land use change
LUC P1: Conversion of logged over forest
LUC P2: Conversion of tropical rainforest
LUC P3: Conversion of peat land rainforest

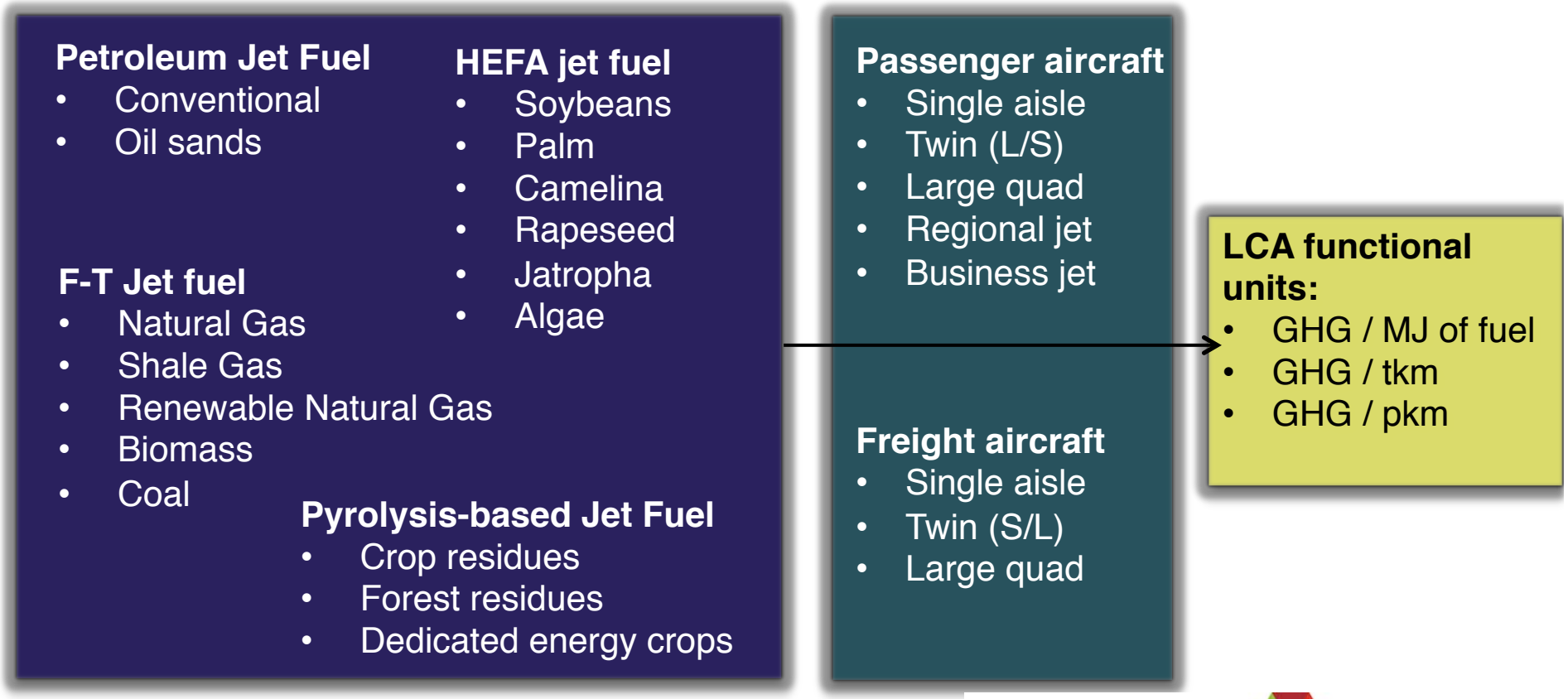


- Emissions from LUC dominate the pathway
- Extremes of no LUC and conversion of highest carbon stock land vary by factor of 30

Outcomes (3 of 4)

PARTNER
10 YEARS
2003-2013

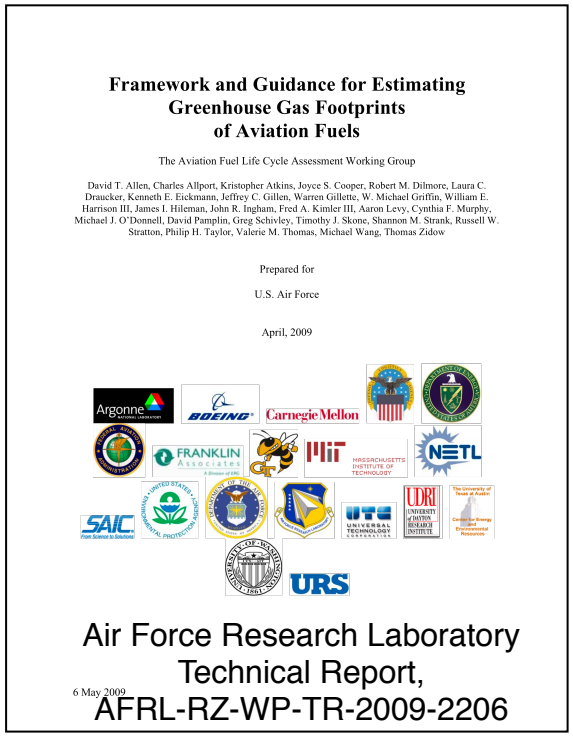
- Jet fuel module for GREET database



Argonne NATIONAL LABORATORY

Outcomes (4 of 4)

PARTNER
10 YEARS
2003-2013



Framework and Guidance for Estimating Greenhouse Gas Footprints of Aviation Fuels

The Aviation Fuel Life Cycle Assessment Working Group

David T. Allen, Charles Allport, Kristopher Atkins, Joyce S. Cooper, Robert M. Dilmore, Laura C. Draucker, Kenneth E. Eickmann, Jeffrey C. Gillen, Warren Gillette, W. Michael Griffin, William E. Harrison III, James I. Hileman, John R. Ingham, Fred A. Kimler III, Aaron Levy, Cynthia F. Murphy, Michael J. O'Donnell, David Pamplin, Greg Schivley, Timothy J. Skone, Shannon M. Strank, Russell W. Stratton, Philip H. Taylor, Valerie M. Thomas, Michael Wang, Thomas Zidow

Prepared for

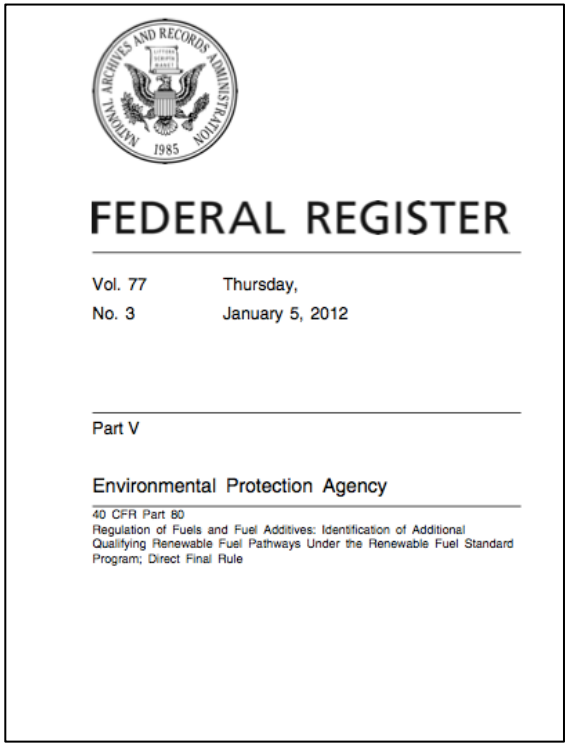
U.S. Air Force

April, 2009

6 May 2009

Air Force Research Laboratory Technical Report, AFRL-RZ-WP-TR-2009-2206

Guidance document on LCA



FEDERAL REGISTER

Vol. 77 No. 3 Thursday, January 5, 2012

Part V

Environmental Protection Agency

40 CFR Part 80
Regulation of Fuels and Fuel Additives: Identification of Additional Qualifying Renewable Fuel Pathways Under the Renewable Fuel Standard Program; Direct Final Rule

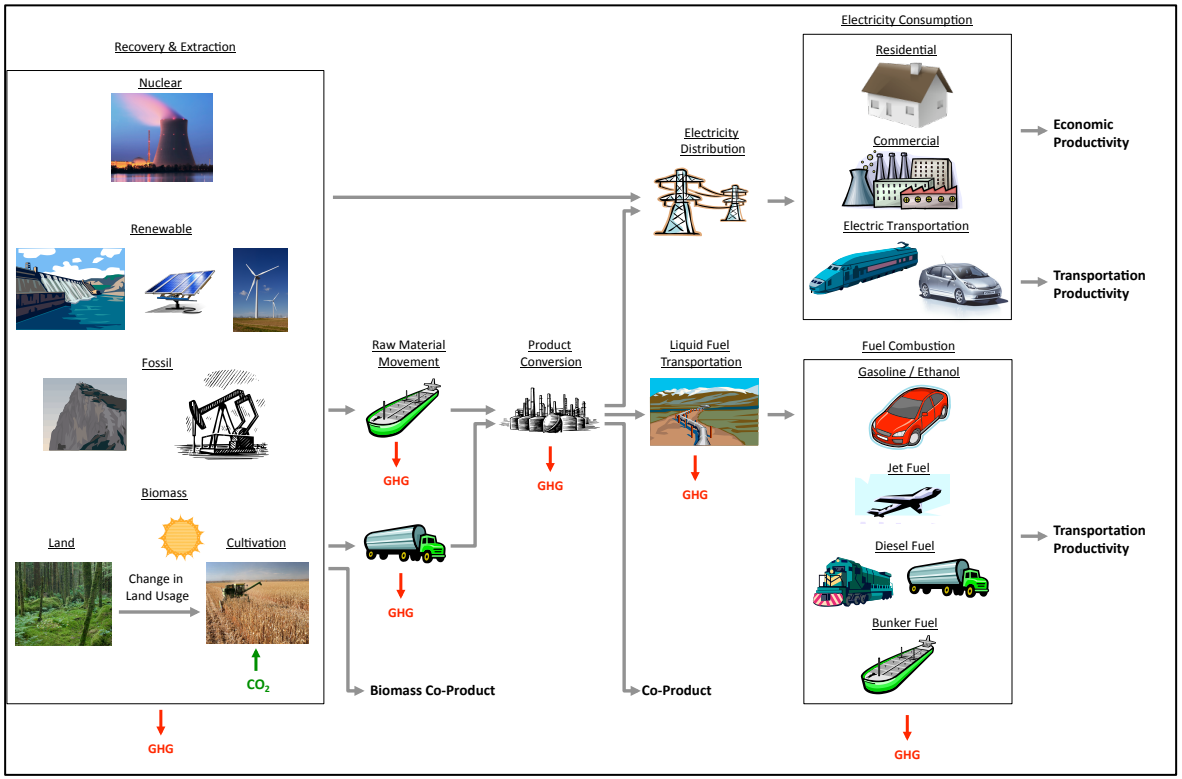
EPA: Identification of additional pathways for RFS2

Ongoing work

PARTNER
10 YEARS
2003-2013

- Further enhancing understanding of properties of alternative fuels' sustainability, especially in terms non CO_2 emissions and related climate and public health impacts

- Understanding and quantifying trade-offs among metrics, pathways and usages



Interfaces and Communications

PARTNER
10 YEARS
2003-2013

- Publications
  - 7 peer-reviewed publications, 6 MIT theses, 25+ conference and workshop presentations
- Collaboration within PARTNER
  - Collaboration with projects on emission measurements (P20 and P37) and policy-related projects (P27 and P31)
- External collaborations
  - Industry: e.g. Pratt & Whitney, Boeing, UOP, Shell, Gevo
  - Research: e.g. Argonne National Laboratory, Volpe Transportation Center, MIT's Joint Program on the Science and Policy of Global Change, USDA, EPA, DOE, Rand Corporation, Metron
  - Initiatives: e.g. Commercial Aircraft Alternative Fuels Initiative (CAAFI), Sustainable Way for Alternative Fuel and Energy in Aviation (SWAFEA)

Summary on lifecycle GHG work

PARTNER
10 YEARS
2003-2013

- Life-cycle assessment is critical to determine whether a potential alternative jet fuel will reduce GHG emissions
- Jet fuels from non-conventional fossil sources has been shown to have higher GHG emissions than jet fuel from conventional crude
- Renewable jet fuels exist that could significantly reduce life-cycle GHG emissions compared to conventional jet fuel if adverse land-use change is avoided
- If land use changes are incurred, biofuels can have life-cycle GHG emissions that are many times worse than conventional jet fuel
- Ongoing work focuses on incorporating competitive uses for biomass and environmental impacts beyond CO_2(e)

Contributors

PARTNER
10 YEARS
2003-2013

- **MIT Students:** Russ Stratton (former), Nick Carter (former), Michael Bredehoeft (former), Wilfried Mofor (former), Kristy Bishop (former), Pearl Donohoo (former), Hsin Min Wong (former), Mark Staples, Parth Trivedi, Jacob Ames and Mitch Withers

- **MIT Faculty & Research Staff:** Ian Waitz, Jim Hileman (former), John Reilly, Sergey Paltsev, Malcom Weiss, Hakan Olcay, Matthew Pearlson, Gonca Seber, Christoph Wollersheim, Kenneth Strzepek, Robert Malina and Steven Barrett

- **Project managers**: Warren Gillette, Carl Ma and Nathan Brown (FAA), Daniel Baniszewski (DLA Energy), Bill Harrison and Tim Edwards (AFRL)